OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL COVER SHEET
Complete Only Applicable Items

1. QA: QA

Page: 1 of: 89

2. ☒ Analysis — Check all that apply

Type of Analysis:
- ☐ Engineering
- ☐ Performance Assessment
- ☒ Scientific

Intended Use of Analysis:
- ☐ Input to Calculation
- ☒ Input to another Analysis or Model
- ☐ Input to Technical Document
- ☒ Input to other Technical Products

Describe use:

Input to analyses of fault displacement effects on emplacement drifts and transport in the unsaturated zone. Also input to analysis of disruptive events and processes.

3. ☐ Model — Check all that apply

Type of Model:
- ☐ Conceptual Model
- ☐ Abstraction Model
- ☐ Mathematical Model
- ☐ System Model
- ☐ Process Model

Intended Use of Model:
- ☐ Input to Calculation
- ☐ Input to another Model or Analysis
- ☐ Input to Technical Document
- ☐ Input to other Technical Products

Describe use:

4. Title:

Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada.

5. Document Identifier (including Rev. No. and Change No., if applicable):

ANL-CRW-GS-000003 REV 00

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Block 10: Debra Bryan replaced Richard Quittmeyer as Lead/Supervisor.

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OFFICE OF CIVILIAN RADIOACTIVE WASTE MANAGEMENT
ANALYSIS/MODEL REVISION RECORD
Complete Only Applicable Items

2. Analysis or Model Title:

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CONTENTS

Page

FIGURES

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TABLES

Page

ACRONYMS

AAR	Arabasz, Anderson and Ramelli (team)
AD	average displacement
AMR	Analyses and Models Report
ASM	Ake, Slemmons and McCalpin (team)
CM	Configuration Management
CRWMS	Civilian Radioactive Waste Management System
DE	Disruptive Events (process model report)
DFS	Doser, Fridrich and Swan (team)
DOE	U.S. Department of Energy
ESF	Exploratory Studies Facility
FEPs	features, events, and processes
GM	ground motion (experts or Facilitation Team)
M&O	Management and Operating Contractor
M_{max}	maximum magnitude
M_w	moment magnitude
MD	maximum displacement
MRE	magnitude-distance-epsilon
NRC	U.S. Nuclear Regulatory Commission
Pa	probability of activity
PGA	peak ground acceleration
PGV	peak ground velocity
P[s]	probability of being seismogenic
PSHA	probabilistic seismic hazard analysis
QA	Quality Assurance
QARD	Quality Assurance Requirements and Description
RA	rupture area
RF	reduction factor
RL	rupture length
RYA	Rogers, Yount and Anderson (team)
SA	spectral acceleration
SBK	Smith, Bruhn and Knuepfer (team)
SDO	Smith, de Polo and O'Leary (team)
SR	slip rate
SRL	surface-rupture length
SSC	structure, system, and component
SSFD	seismic source and fault displacement
TSPA	total system performance assessment
USGS	U.S. Geological Survey

1. PURPOSE

The purpose of this Analyses and Models Report (AMR) is to summarize the probabilistic seismic hazard analysis (PSHA) for the Yucca Mountain site such that it can be used in preparing the *Disruptive Events* (DE) *Process Model Report* (CRWMS M&O 2000a). The PSHA, *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada* (Civilian Radioactive Waste Management System [CRWMS] Management and Operating Contractor [M&O] 1998a), was a 4-year multidisciplinary project that assessed both ground motion and fault displacement hazards. The DE process model report is one of a group of documents summarizing models and data that will form the technical basis for the total system performance assessment (TSPA) supporting the Site Recommendation. The DE process model report will describe analyses of seismic and igneous events and their effects for use in the TSPA for Site Recommendation. In addition to supporting the DE process model report directly, this AMR also furnishes indirect support to:

- Analyses addressing the effects of ground motion and fault displacement for the postclosure period
- An analysis of seismic-related features, events, and processes (FEPs) to determine whether they should be included in the TSPA for Site Recommendation
- An evaluation of the extent to which the U.S. Nuclear Regulatory Commission's (NRC) subissues and acceptance criteria associated with the Seismicity and Structural Deformation and other key technical issues have been addressed (NRC 1999).

Results of the PSHA also support development of seismic inputs for preclosure design.

Seismic hazards potentially affecting the Yucca Mountain site consist of vibratory ground motion and fault displacement. Consideration of these hazards in TSPA depends on their likelihood of occurrence and their effects on engineered items and the natural system. Likelihood of occurrence is addressed in this AMR. Analyses to assess ground motion effects are being carried out in support of Engineered Barrier System, Waste Package, and Waste Form process model reports. Fault displacement effects are addressed in the analyses *Fault Displacement Effects on Transport in the Unsaturated Zone* (CRWMS M&O 2000b) and *Effects of Fault Displacement on Emplacement Drifts* (CRWMS M&O 2000c), which support the DE process model report. Results on likelihood of occurrence and effects will then form part of the basis for an analysis, *Disruptive Events FEPs* (CRWMS M&O 2000d), which will determine whether seismic-related FEPs need to be included in TSPA for Site Recommendation. Therefore, one purpose of this AMR is to summarize the PSHA results such that they can be used in these subsequent analyses to evaluate effects of seismic hazard and their impact on performance.

For postclosure, the seismic hazard results are being used to evaluate whether future ground motions or fault displacements contribute to any repository events that occur with a probability greater than 1 in 10,000 in 10,000 years, and that have significant effects on overall performance. Consistent with U.S. Department of Energy (DOE) interim guidance (Dyer 1999, Section 63.2), for the purpose of postclosure performance assessment, an event in this regard is considered in this report to be the failure of a structure, system, or component (SSC) to perform its functional goal. A seismic event then is the failure of an SSC to perform its intended functional goal under ground shaking or fault displacement loading during the postclosure period of interest.

Although simplified analyses are used to support TSPA for Site Recommendation, ultimately analyses to determine and describe seismic ground motion events for input to performance assessment will involve the development of fragility curves (frequency of failure as a function of ground motion level) for critical SSCs. Depending on final design choices, such SSCs might include emplacement drifts, drip shields, and waste packages. The hazard results can be used to develop a suite of ground motion time histories for different magnitude earthquakes that can be used in analyses to develop the fragility curves. The hazard curves then can be convolved with the fragility curves to determine a probability distribution for the frequency of failure of the SSC to perform its functional goal. Convolution involves multiplication of the hazard and fragility curves and integrating over an appropriate range of ground motion levels to describe the probability of unacceptable performance. For SSCs designed to NRC seismic design requirements, as will be the case for the Yucca Mountain facility (YMP 1997a), integration to about 1.5 to 3 times the seismic design ground motion level appropriately captures the probability of unacceptable performance (Kennedy and Ravindra 1984). These analyses will support updated evaluations of seismic-related FEPs for inclusion or exclusion in TSPA. If FEPs are included, the analyses will also provide the basis for how they are treated. Thus, the ground motion hazard curves summarized in this AMR provide the basis for postclosure analyses.

Ground motion hazard results are also being used to develop preclosure seismic design inputs for the potential geologic repository at Yucca Mountain. The ground motion hazard results form the basis for identifying controlling design earthquakes and controlling ground motion spectra appropriate for the proposed Geologic Repository Operations Area (Dyer 1999). The location-specific inputs for seismic design of specific SSCs are developed from the controlling design ground motions by taking into account the effects of near-surface soil and rock. The inputs are then used in analyses to design SSCs that accommodate the ground motion such that safety and waste isolation functions are preserved to the extent that the health and safety of the public is maintained. Although supported by this AMR, preclosure seismic issues are not part of the scope of the DE process model report. Rather, these issues are addressed in a series of three topical reports (see Section 6.1 for further discussion of these reports).

Fault displacement hazard curves are also being used for postclosure and preclosure analyses. For postclosure performance assessment, the fault displacement hazard curves can be used in a fashion similar to that for ground motion to identify repository events for input to FEP evaluation and postclosure performance assessment. The fault displacement hazard curves thus provide input to response analyses of the engineered barrier system, waste package system, and natural system in response to fault displacement. Convolving the responses of these repository components and the natural system with the fault displacement hazard curves describes event frequencies for input to the performance assessment. For preclosure seismic design, the fault displacement hazard curves will be used as a basis for determining in which portions of the repository waste emplacement area the probability of fault displacement is so low that it does not need to be considered in design. Also the fault displacement hazard results are being used as input to analyses to determine appropriate setback distances of SSCs from primary faults in order to provide reasonable assurance that they will maintain their intended waste isolation and containment functions. For any safety-related SSCs that cannot be located such that they avoid significant faults, the hazard curves will serve as a basis to determine the level of fault displacement that must be accommodated in preclosure engineering design.

A final purpose of this AMR is to summarize how tectonic models for the Yucca Mountain site were considered and evaluated in the PSHA. The PSHA employed an expert elicitation process to evaluate the extensive database of relevant information pertaining to the characterization of seismic sources, fault displacement, and ground motion at Yucca Mountain. The experts were provided with available information on tectonic models proposed for the Yucca Mountain vicinity. They used that information in weighting the likelihood of different models applying to the site. Thus, for seismic hazard assessment, no single model is selected for Yucca Mountain Project use, but rather uncertainty in our understanding of the tectonic framework for the site is quantitatively assessed as part of the hazard analysis. This AMR provides a summary of those tectonic model assessments for use in the DE process model report and in performance assessment.

To accomplish the above purposes, this AMR has the following objectives as outlined in *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada* (Development Plan) (CRWMS M&O 1999a):

- Summarizing the PSHA process and the use of experts to define inputs and characterize uncertainties for seismic hazard computation
- Summarizing the conceptual framework for seismicity and structural deformation at Yucca Mountain based on the interpretations of the PSHA experts and other available information (with emphasis on how uncertainty in tectonic models and other relevant input parameters was incorporated in the hazard results through the PSHA process)
- Summarizing vibratory ground motion and fault displacement hazard results at Yucca Mountain.

As a synthesis of the PSHA, this AMR has no limitations except those implicit in the PSHA; these are discussed in Section 6.1.5.

2. QUALITY ASSURANCE

Development of this AMR was evaluated in accordance with QAP-2-0, *Conduct of Activities*, and was determined to be quality affecting and subject to *Quality Assurance Requirements and Description* (QARD) (DOE 2000). This is documented in activity evaluations for Work Packages 14016105M5 (CRWMS M&O 1999b) and 1401213DM1 (Wemheuer 1999). Accordingly, this AMR was developed in accordance with AP-3.10Q, *Analyses and Models*. Other applicable DOE Office of Civilian Radioactive Waste Management Administrative Procedures are identified in the Development Plan (CRWMS M&O 1999a). In accordance with QAP-2-3, *Classification of Permanent Items,* there are no permanent items directly associated with this AMR.

3. COMPUTER SOFTWARE AND MODEL USAGE

No software was used to directly support information reported in this AMR. Nonqualified software (e.g., Microsoft Word, Version 97; Aldus Freehand, Version 8) was used to perform support activities, such as document and figure preparation, but output from this software was not used in quality affecting work. Thus, this software is exempt from qualification requirements of AP-SI.1Q, *Software Management,* Rev. 2, ICN 4. Refer to Section 6.2 and Attachment II for discussion of software used for PSHA calculations.

4. INPUTS

4.1 DATA AND PARAMETERS

This AMR contains two basic types of input data that all came from the PSHA (CRWMS M&O 1998a). These include the experts' interpretations and the results for the fault displacement hazard assessment (Table 1), and the experts' interpretations and results for the ground motion hazard assessment (Table 2). For the ground motion assessment, the experts' interpretations included both the seismic source characterization and the ground motion attenuation characterization (Table 2). The experts' interpretations are based on an extensive database (Appendix B of CRWMS M&O 1998a). Both the experts' interpretations and the hazard results as described in the PSHA are qualified by virtue of the expert elicitation process. All of these inputs are discussed further in Section 6, including explanation of terms and parameters. The Q status of the input data is provided in the Document Input Reference System.

4.2 CRITERIA

This AMR complies with Part 63.2 DOE interim guidance (Dyer 1999). Subparts of the interim guidance that apply to this analysis are those pertaining to the characterization of the Yucca Mountain site (Subpart B, Section 15), the compilation of information regarding geology of the site in support of the License Application (Subpart B, Section 21 (c) (1) (ii)), and the definition of geologic parameters and conceptual models used in performance assessment (Subpart E, Section 114 (a)).

At this time, criteria in the form of specific System Description Documents have not been identified that apply to this AMR. The PSHA Project was conducted following the guidance provided in *Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain, Nevada* (YMP 1997b) and the process was generally consistent with NUREG/CR 6372 (Budnitz et al. 1997) and NUREG 1563 (Kotra et al. 1996). This PSHA approach has been accepted in principle by the NRC (Bell 1996).

4.3 CODES AND STANDARDS

No specific formally established codes or standards have been identified that apply to this AMR or the PSHA for Yucca Mountain.

Table 1. Input Data Used from
the PSHA Fault Displacement Hazard Assessment

Description	Data Tracking Number
Fault Displacement Characterization for Nine Demonstration Points	MO0004MWDRIFM3.002
Fault Displacement Hazard Results for Nine Demonstration Points	MO0004MWDRIFM3.002

Table 2. Input Data Used from
the PSHA Ground Motion Hazard Assessment

Description	Data Tracking Number
Experts' Interpretations Feeding into the PSHA Calculations:	
Seismic Source Characterization (includes tectonic models, fault sources, and areal source zones)*	MO0004MWDRIFM3.002
Ground Motion Attenuation Characterization (includes median ground motions and uncertainties for normal and strike-slip earthquakes)*	MO0004MWDRIFM3.002
PSHA Ground Motion Hazard Results:	
Peak Ground Accelerations (PGAs) (including mean and fractile values for horizontal and vertical motions)	MO0004MWDRIFM3.002
Peak Ground Velocities (PGVs) (including mean and fractile values for horizontal and vertical motions)	MO0004MWDRIFM3.002
Spectral Accelerations (SAs) (including mean and fractile values for horizontal and vertical motions)	MO0004MWDRIFM3.002

* Note that these inputs (the seismic source characterization and the ground motion attenuation characterization) are linked together in the same logic tree data files submitted to the Automated Technical Data Tracking System.

5. ASSUMPTIONS

As the analysis for this AMR consists of the translation, summary, and documentation of the PSHA Project, no assumptions were made in this summary. Key assumptions were made, however, in the PSHA process and they are summarized in Section 6.4.

6. ANALYSIS/MODEL

The analysis for this AMR is the translation, summary, and documentation of the PSHA Project. There were no models developed for this AMR. The following sections first briefly describe the necessary background information on the PSHA Project, computer software, description of input, assumptions, methodology, and finally results for calculating both the ground motion and fault displacement hazard assessments in the PSHA Project. Sensitivity analyses for the PSHA are also discussed in this section. Substantiation of models in the PSHA was carried out by experts through the expert elicitation and review process during the project.

6.1 BACKGROUND FOR THE PSHA PROJECT

Yucca Mountain is located about 160 km northwest of Las Vegas, in the southern Great Basin portion of the Basin and Range province. The region is tectonically active at a low to moderate strain rate (CRWMS M&O 1998b, Section 12.3; Savage et al. 1999) and is characterized by the presence of abundant late-Quaternary faults and a moderate level of historical seismicity (Figure 1), with the occurrence of relatively infrequent earthquakes up to about moment magnitude (M_w) 7.5.

The Nuclear Waste Policy Act of 1982, as amended in 1987, assigns to the DOE the responsibility of evaluating Yucca Mountain as a potential geologic repository to site the nation's first permanent disposal facility for spent nuclear fuel and high-level radioactive waste. As part of the seismic performance aspect of this effort, the U.S. Geological Survey (USGS) and the CRWMS M&O jointly performed the PSHA Project. The PSHA Project was initiated in August 1994, was on hiatus from October 1995 to September 1996, resumed in October 1996, and concluded in June 1998 with the issuance of the PSHA report (CRWMS M&O 1998a).

The overall approach that the DOE has undertaken to address potential seismic hazards at Yucca Mountain is documented in three topical reports: *Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain* (Topical Report I) (YMP 1997b) and *Preclosure Seismic Design Methodology for a Geologic Repository at Yucca Mountain* (Topical Report II) (YMP 1997a). A planned third seismic topical report will document the results of both the PSHA Project and the Seismic Design Project. The methodology adopted and used in the PSHA Project is described in Topical Report I. This methodology is generally consistent with state-of-the-practice guidance provided by the Senior Seismic Hazard Analysis Committee (Budnitz et al. 1997). The methodology and acceptance criteria used by the DOE to determine the preclosure seismic design of repository SSCs is described in Topical Report II.

6.1.1 Objectives

The objective of the PSHA was to provide ground shaking and fault displacement hazard results for both preclosure (100 years) design determination and postclosure (10,000 years or more) performance assessment. The governing guidance (Dyer 1999) specifies consideration of two categories of preclosure events in the seismic design of the repository SSCs and radiological safety. Category-1 events are expected to occur one or more times during the preclosure operational period of the facility. Design for these events is required to provide for protection of worker safety and for seismic design for ground shaking, with the target hazard established at 10^{-3} annual exceedance probability (YMP 1997a). Design for Category-2 events is required to provide for radiological safety protection of the public during the preclosure period. Ground-shaking seismic design parameters for these events will be based on hazard at an annual exceedance probability of 10^{-4} (YMP 1997a). As experience with the design of engineered structures for fault displacement is limited, corresponding target hazard levels for determining fault displacement preclosure designs are 10^{-4} and 10^{-5} for Category-1 and Category-2 events, respectively (YMP 1997a). Although criteria are defined for fault displacement design, the primary approach will be to avoid faults capable of significant movement in laying out a repository. For additional discussion of how the PSHA Project relates to ongoing preclosure and postclosure seismic design efforts, see CRWMS M&O (1998a, Section 1.2) and Topical Report II (YMP 1997a).

For postclosure, the objective of the PSHA was to provide hazard results for evaluating whether future ground motions or fault displacements contribute to any repository events that occur with a probability greater than 1 in 10,000 in 10,000 years, and that have significant effects on overall performance. Note that an event as applied here to postclosure assessment does not refer to an earthquake or ground motion event. Instead, an event is the failure of an SSC to perform its functional goal (Dyer 1999, Section 63.2).

6.1.2 Overview

As shown on Figure 2, the main activities comprising the PSHA process were (1) multiple-expert evaluation and characterization of seismic sources, including the characterization of potential fault displacement; (2) multiple-expert evaluation and characterization of vibratory ground motion attenuation, including earthquake source, wave propagation path, and rock site effects; and (3) computation of hazard results for both fault displacement and vibratory ground motion. The experts provided alternative evaluations to characterize uncertainties in their interpretations. Based on these alternative interpretations, hazards were calculated and expressed as the annual probability at which levels of ground motion or fault displacement will be exceeded.

The fault displacement hazard was evaluated at nine locations within the Yucca Mountain site area (Figure 3). These locations were selected to span the range of known faulting conditions within the area of the proposed repository and the associated surface facilities, based on various surface (e.g. Day et al. 1998) and subsurface studies (e.g. Beason et al. 1996). Faulting conditions ranged from primary block-bounding faults to unfaulted rock, and included sites on secondary faults, and on fractures that were assigned displacement histories representing displacement conditions encountered in the Exploratory Studies Facility (ESF). The specific conditions at the nine sites are described in Section 6.3.4. The vibratory ground motion was evaluated at a “reference rock outcrop” located near the center of the proposed repository (Figure 3). The reference rock outcrop is defined as free-field ground surface, at the elevation of the proposed repository, 300 m below the repository ground surface at Point A on Figure 4. The basis of selection and specific properties of this reference site are discussed further in Section 6.3.3.1.1.

The assessment of seismic hazards at Yucca Mountain relied upon the results of scientific investigations carried out over the past 20 years. Building upon earlier investigations of the Nevada Test Site region, studies of the Yucca Mountain site have included (1) evaluations of faults within about 100 km for evidence of Quaternary activity; (2) detailed paleoseismic fault-trenching studies of active faults near Yucca Mountain to determine the history and characteristics of past earthquakes; (3) monitoring of contemporary seismicity; (4) compilation of a catalog of historical and instrumentally recorded earthquakes in the Yucca Mountain region; (5) development of ground motion attenuation relationships for extensional tectonic regimes, which includes the Yucca Mountain region; (6) investigation of local site attenuation characteristics; (7) numerical modeling of ground motion from scenario earthquakes; (8) evaluation of the tectonic stresses from hydrofracture measurements and earthquake focal mechanisms; (9) collection and analysis of geophysical data to assess tectonic models and identify subsurface faults; and (10) collection and analysis of geodetic data to measure ongoing crustal deformation. Results of many of these studies are summarized in Whitney (1996). This extensive database, in addition to the numerous studies performed by nonproject scientists and the already existing literature and information, formed the basis for the Yucca Mountain seismic hazards analyses. For a complete bibliography of material supplied to the PSHA experts, see Appendix B of CRWMS M&O (1998a).

The method to calculate ground-shaking hazard at a site is well established in the literature (Cornell 1968; McGuire 1978, 1995). Basic inputs required to perform a ground-shaking hazard calculation at a site are (1) an interpretation of seismic sources that contribute to the site hazard, from which conditional probability distributions of distance of earthquakes from the site can be obtained; (2) an interpretation of earthquake recurrence for each source, including the mean annual rate of occurrence and magnitude distribution of earthquakes; and (3) an evaluation of ground-shaking attenuation for the site region, including the mean and standard deviation of ground-shaking amplitude as a function of magnitude and distance. These inputs constitute an interpretation of the seismotectonic environment of the site. Given the input evaluations, the hazard calculation method integrates over all values of the variables and obtains an estimate of the mean probability of exceedance of any ground-shaking amplitude at the site. A plot of these results is the well-known seismic hazard curve. The hazard curve quantifies the randomness or aleatory uncertainty of the earthquake occurrence and ground-shaking attenuation. The calculation method can thus be thought of as an aleatory seismic hazard model.

In addition to the aleatory uncertainty of the seismic hazard, however, is epistemic uncertainty about the seismotectonic environment of a site. Epistemic uncertainty is due to scientific uncertainty about earthquake processes and ground-shaking attenuation and the incompleteness of available data for evaluating these processes. Significant advances in development of methodology to quantify epistemic uncertainty in seismic hazard have been made in the past 20 years (EPRI [Electric Power Research Institute] 1986, Volume 1; Budnitz et al. 1997). These advances involve the development of alternative interpretations of the seismotectonic environment of a site by multiple experts and the structured characterization of epistemic uncertainty. Evaluations by multiple experts are made within a structured expert elicitation process designed to minimize uncertainty due to uneven or incomplete knowledge and understanding (Budnitz et al. 1997). The weighted alternative interpretations are expressed by use of logic trees (EPRI 1986, Volume 1). Each pathway through the logic tree represents a weighted interpretation of the seismotectonic environment of the site for which an aleatory seismic hazard curve is computed. The result of computing the hazard for all pathways is a distribution of hazard curves representing the full aleatory and epistemic uncertainty in the hazard at a site. For further discussion of aleatory and epistemic uncertainty, see Section 6.5.2.

Elements of this methodology as applied in the PSHA for the proposed Yucca Mountain facility are shown on Figure 2. Epistemic uncertainty was evaluated by six teams of three earth science experts, who characterized seismic sources in the Yucca Mountain site region (within a distance of about 100 km) and fault displacement potential at the nine demonstration points, and by seven ground motion (GM) experts, who characterized ground motion attenuation in the site region (see next section for additional discussion of experts and project personnel). Details on the criteria and process for selecting PSHA experts are provided in Section 2.3 of CRWMS M&O (1998a).

Interpretations for hazard assessment were coordinated and facilitated through a series of workshops. Each workshop was designed to accomplish a specific step in the elicitation process and to ensure that the relevant data were being appropriately considered and integrated. An important goal in the elicitation process was to reduce variability in interpretations that is due to a lack of common understanding of the available data and probabilistic models that are used in the analysis. The integrity of the seismic hazard results rests principally on the scientific quality and thoroughness of interpretations of the seismotectonic environment input to the hazard calculation. It is, therefore, important that the methodology should not constrain the experts' input interpretations. To satisfy this important requirement, the methodology was modified to accommodate interpretations specific to the Yucca Mountain site as required. These modifications were incorporated into the computer code FRISK88 (FRISK 88 V2.0, 10139-2.0-00) (Section 6.2) that was used to compute the ground-shaking hazard at the Yucca Mountain site. In addition, the code was modified to compute fault displacement hazard using multiple interpretations of fault displacement potential as input. The final PSHA results were presented as mean, median, and fractile hazard curves representing the total uncertainty (epistemic and aleatory) in input interpretations.

6.1.3 Project Organization

The major components and personnel of the PSHA Project organization are shown on Figure 5 and Table 3. Four technical teams were formed to plan, organize, and lead the technical workshops, facilitate the experts interpretations, and perform hazard calculations: (1) Seismic Source and Fault Displacement (SSFD) Facilitation, (2) GM Facilitation, (3) Data Management, and (4) PSHA Calculations. A Review Panel was formed to provide technical review and guidance to the project. Members of the Review Panel were selected to provide expertise in PSHA methodology and the required input evaluations. The Review Panel provided ongoing review throughout the performance of the PSHA. Panel members attended all workshops, made informal comments during the workshops, and made formal recommendations following each workshop. This participatory review allowed the project to make adjustments and take corrective actions throughout the performance of the work. The Panel also reviewed the draft final report and made formal recommendations.

Table 3. SSFD and GM Experts

SSFD Expert Teams	Affiliation
Team AAR:	
Walter J. Arabasz	University of Utah
R. Ernie Anderson	U.S. Geological Survey
Alan R. Ramelli	Nevada Bureau of Mines & Geology
Team ASM:	
Jon P. Ake	U.S. Bureau of Reclamation
D. Burton Slemmons	Consultant
James McCalpin	GEO-HAZ Consulting, Inc.
Team DFS:	
Diane I. Doser	University of Texas, El Paso
Christopher J. Fridrich	U.S. Geological Survey
Frank H. (Bert) Swan	Geomatrix Consultants, Inc.

SSFD Expert Teams	Affiliation
Team RYA:	
Albert M. Rogers James C. Yount Larry W. Anderson	GeoRisk Associates, Inc. U.S. Geological Survey U.S. Bureau of Reclamation
Team SBK:	
Kenneth D. Smith Ronald Bruhn Peter L. Knuepfer	University of Nevada, Reno University of Utah Binghamton University
Team SDO:	
Robert B. Smith Craig dePolo Dennis W. O'Leary	University of Utah Nevada Bureau of Mines & Geology U.S. Geological Survey
GM Experts	**Affiliation**
John G. Anderson	University of Nevada, Reno
David M. Boore	U.S. Geological Survey
Kenneth W. Campbell	EQE International Inc.
Arthur F. McGarr	U.S. Geological Survey
Walter J. Silva	Pacific Engineering & Analysis
Paul G. Somerville	URS Greiner Woodward Clyde
Marianne C. Walck	Sandia National Laboratories

Note: Teams are named by using the first letter of each member's last name.

6.1.4 Quality Assurance

The PSHA Project was performed under the USGS Quality Assurance (QA) Program developed during that time (August 1994 to June 1998) for the Yucca Mountain Project. This included YMP-USGS-QMP-3.16, Rev 0, *Scientific Expert Elicitation* (USGS 1996), and a latter modification (Rev 0-M1; USGS 1998). The key elements of the program applicable to PSHA were personnel qualifications and training, scientific expert elicitation, software controls, records management, and data management. Records were submitted to the Records Processing Center as per YMP-USGS-QMP-3.16. Personnel qualifications files consisting of position descriptions, resumes, and verification statements were collected for PSHA Project members including the Management Team, Review Panel, and technical teams. Training in expert elicitation and in the applicable procedures was provided via workshops and reading assignments.

At the time that the PSHA was performed, the QARD did not specify requirements applicable to scientific expert elicitation. However, the USGS developed YMP-USGS-QMP-3.16, which did include appropriate requirements for scientific expert elicitation. Revision 8 of the QARD (DOE 1998) became effective June 5, 1998 at the end of the PSHA project and it included requirements for scientific expert elicitation in Appendix C. These requirements were based on NUREG-1563, *Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program* (Kotra et al. 1996), and implementation of the PSHA Project was generally consistent with NUREG-1563. One potential difference in the PSHA project was the approach to documenting changes in the experts' interpretations prior to finalizing the results. The QARD and the NUREG require the experts to document the reasons for any modifications to their interpretations. Within the structured expert elicitation process implemented for the PSHA Project, this NUREG requirement was considered to be implicitly met by the workshop summaries (CRWMS M&O [1998a], Appendices C and D, workshop summaries). The summaries contain descriptions of preliminary evaluations by experts. During the PSHA project, additional specific requirements to justify evolving evaluations were considered by the PSHA Management Team to have the unacceptable consequence of anchoring and biasing the experts' evaluations. During a QA audit of the USGS, DOE's QA Office compared the USGS procedure, the PSHA Project Plan, and implementation of the NUREG guidance to the then-draft QARD requirements (DOE 1997). The audit team accepted this position and justification by the PSHA Management Team on explicitly documenting changes to the experts' evaluations.

6.1.5 Limitations

The PSHA is based on the information and data available at the time of the evaluations (June 1998). The geology and seismology of Yucca Mountain have been well-studied and the PSHA experts were provided an extensive and comprehensive information base from which to derive their interpretations. As part of their evaluations, the experts provided not only their best estimates of seismic source and ground motion parameters but also possible ranges in these parameters and their associated uncertainties as allowed by the available data. Thus, these interpretations should capture the full range of models and uncertainty in their evaluations considering the extensive available data. As data uncertainty was specifically considered by the experts, any new data are not expected to significantly impact the experts' interpretations. Additionally, a procedure is currently in place, AP-AC.1Q, *Expert Elicitations*, by which new data that might have significant relevance to the PSHA will be evaluated and its potential impact assessed.

The ground motion hazard has been computed for a location at the approximate center of the site area on a reference rock outcrop where a kappa of 0.0186 sec and shear-wave velocity of 1,900 m/sec was assumed based on limited site-specific data (Sections 6.3.3.1.1. and 6.4). Thus, the hazard results are strictly only valid for this reference site condition. An analysis is ongoing to develop preliminary seismic design ground motions for the repository, the top of the tuff above the repository, and the Waste Handling Building (CRWMS M&O 2000e). The control point hazard is generally applicable for any location within the area of the proposed repository, with this site condition, although small differences in the hazard are expected near the edges of the proposed repository area.

6.2 PSHA COMPUTER SOFTWARE

Within the PSHA process, software QA requirements were applicable only to the computer codes used for calculating the ground shaking and fault displacement hazards, as per YMP-USGS-QMP 3.16 (USGS 1996). Any software used by the experts in developing their interpretations was considered part of the expert elicitation process and was thus exempted from QARD software requirements.

Following the experts' evaluations, the calculations performed as part of the PSHA Project were executed using a modified version of FRISK88, a software package, developed by Risk Engineering that is accessible through Yucca Mountain Configuration Management (CM). The appropriate software configuration identifiers are shown in Table 4. All of the software used for seismic hazard calculations was originally documented and verified in compliance with YMP-USGS-QMP 3.03, *Software* (USGS 1997). The full life cycle plan activities and documentation included completion of the following:

- Software identification form
- Software CM form
- Requirements specification
- Validation plan
- Design description
- User documentation
- Software validation report
- Review and verification documentation
- Documentation for operations and maintenance activities

Table 4. Software Used in the PSHA Project Calculations

Computer Code or Subroutine	Version	USGS Tracking Number	CM Software Tracking Number or Reference	Computer Type
PREP88 (code)	1.0	ESP0019.01	10138-1.0-00	HP 735
POST88 (code)	1.0	ESP0020.01	10136-1.0-00	HP 735, PC
MRE88 (code)	1.0	ESP0021.01	10140-1.0-00	HP 735
DPREP (code)	1.0	ESP0026.01	10141-1.0-00	HP 735
DRISK (code)	1.0	ESP0025.01	10137-1.0-00	HP 735
FRISK88 (code)	2.0	ESP0018.01	10139-2.0-00	HP 735, PC
MEAN (subroutine)	1.0	ESP5.42	Toro (1998)	HP 735
CMB-FRAC (subroutine)	1.0	ESP5.43	Toro (1998)	HP 735

The software was appropriate for the application and was used only within the range of validation. Recently, the qualification status of all of the computer codes has been reverified under AP-SI.1Q, *Software Management*, Rev. 1, ICN O. The verification of the two subroutines, MEAN and CMB-FRAC, can be found within Toro (1998). Attachment II contains further description and explanation of the software used in the PSHA calculations.

6.3 PSHA INPUTS

There are three basic types of input developed by the experts for the PSHA: (1) seismic source characterization for the ground motion hazard assessment, (2) ground motion attenuation characterization, and (3) fault displacement characterization. There is overlap between the seismic source characterization for the ground motion assessment and the fault displacement characterization; these are discussed separately below for clarity.

6.3.1 Tectonic Setting and Quaternary Faults at Yucca Mountain

The Quaternary stratigraphy and tectonic setting of Yucca Mountain provides the framework necessary for characterizing seismic sources for both the ground motion and fault displacement hazard assessments. Therefore, the following section briefly describes the tectonic setting, with emphasis on the Quaternary aspects, to provide the needed context for understanding the experts' seismic source characterization. A more detailed discussion of the tectonic setting, stratigraphic framework, and Quaternary paleoseismicity is included in Whitney (1996) and Section 12.3 of the *Yucca Mountain Site Description Report* (CRWMS M&O 1998b).

Yucca Mountain is within the Southern Great Basin of the Basin and Range tectonic province. Tectonically, the Basin and Range is experiencing extensional strain at a low to moderate rate, with low to moderate historical seismicity (Figure 1), and it has a thin crust. Yucca Mountain is located on the south flank of a large Miocene caldera complex. It is considered to be an erosional remnant of a 11.4 to 14.0 million-year-old volcanic apron (Fridrich et al. 1999). Structurally, the mountain is dominated by subparallel north-trending and east-dipping fault blocks. The blocks of ash-flow tuffs are bounded by typical Basin and Range, high-angle, generally west-dipping, normal faults formed by rapid east-west extension during the waning phases of Miocene volcanism. Secondary intrablock faults are common.

Although Basin and Range tectonic structure defines the structural pattern of Yucca Mountain blocks, the whole proposed repository area lies within the Walker Lane, a 100-km-wide structural belt along the western edge of the Basin and Range province. The Walker Lane is characterized by long, northwest-striking and shorter, north-to-northeast-striking, strike-slip faults that accommodate much of the early extension in this region. The peak phase of tectonism took place 12.7 to 11.6 million years ago (middle Miocene); and the region has since experienced declining strain rates. The current pattern of Quaternary deformation mimics the middle Miocene activity, however, at substantially lower rates (Fridrich et al. 1999).

Within a 100-km radius of Yucca Mountain, more than 100 Quaternary faults were identified as potential seismic sources (Figure 6). With the exception of the Death Valley-Furnace Creek-Fish Lake Valley fault system, these faults are interpreted to have low slip rates (SRs) (generally less than 1 mm/yr).

The faults closest to Yucca Mountain are the most important to vibratory ground motion and fault displacement hazards (Figure 6). Within 10 km of the proposed repository 8 of 14 mapped faults show evidence of multiple surface-rupturing earthquakes during the Quaternary. These faults are characterized by trace lengths shorter than 26 km, SRs of 0.001 to 0.05 mm/yr, and average recurrence intervals of 20,000 to 100,000 years (e.g. Whitney 1996). Several faults are spaced only a few km apart and may merge at depth. Paleoevent data modeled from all trench studies suggest that distributed faulting may have been common at Yucca Mountain (Pezzopane et al. 1994).

6.3.2 Seismic Source Characterization for Ground Motion Assessment

The objective of seismic source characterization for the ground-shaking PSHA was to identify and characterize the seismic sources capable of producing earthquakes significant to ground-shaking hazard at the site. Evaluations were conducted following the structured elicitation process that was adopted for the project, which included information assimilation and interpretation workshops and individual team elicitations. The process was facilitated by the SSFD Facilitation Team. The elicitation process included a total of six workshops and a 1-day elicitation meeting with each team (Figure 2). Each SSFD expert team evaluated seismic sources for ground motion and fault displacement hazard computation. The evaluations included alternative interpretations, each weighted to express the teams' uncertainty.

Two basic types of seismic sources were evaluated and characterized by the SSFD experts: fault specific sources and areal seismic source zones. Both local faults (defined here as within about

10 km) and regional faults (to a distance of about 100 km) were evaluated. Areal source zones were defined to represent zones of distributed seismicity not apparently associated with known specific faults, and were also used by some teams to characterize known structures that were not explicitly included as fault-specific seismic sources.

Detailed descriptions of each expert team's seismic source characterization for the ground motion hazard assessment can be found in Appendix E of CRWMS M&O (1998a), and summaries of the evaluations can be found in Section 4.3 of CRWMS M&O (1998a). Table 5 is from Section 4.3 of CRWMS M&O (1998a) and it summarizes the key components of each team's seismic source characterization model, including issues regarding tectonic models and potential seismic sources (areal seismic source zones, regional faults, and local faults). Although tectonic models are not seismic sources per se in the PSHA, they are included in Table 5 because their evaluation was integral to development of seismic source characterization models. Tectonic models provide the framework that can help define or constrain some seismic source parameters, such as maximum seismogenic depths, fault dips, rupture models, and probabilities of activity. Thus, uncertainty in tectonic models was an integral part of seismic source characterization and this uncertainty is fully captured in the hazard results. The following sections discuss the overall treatment of the three main types of seismic sources.

6.3.2.1 Local Fault Specific Seismic Sources

An important part of the evaluations by the SSFD experts focused on characterizing the local fault-specific seismic sources due to their proximity to the site (Figure 6). The local Yucca Mountain faults can be subdivided into three categories: (1) north-striking block-bounding faults, (2) northwest-striking faults, and (3) intrablock faults. The close spacing between faults, their anastomosing pattern, and their relatively short lengths suggest that the local faults may be structurally interconnected either along strike or at depth and, thus, may rupture either partially or fully together.

The local faults were characterized in terms of their rupture behavior, probability of activity, locations, rupture lengths, sense of slip, fault dips, maximum seismogenic depths, maximum magnitude (M_{max}), and rate of activity. Their geometric characterization depended on the experts' evaluations of the tectonic models. Parameters for the most significant local faults are shown in Table 6, and include the block-bounding Paintbrush Canyon, Bow Ridge, Stagecoach Road, and Solitario Canyon faults (Figure 6).

The parameters in Table 6 (also Table 7) generally show the range of preferred values interpreted by the expert teams. Note that because the expert teams varied considerably in their fault characterizations, particularly with regard to interpretations of independent seismic sources and linked or combined fault sources, not all teams characterized the faults individually as listed in Table 6. Approaches used to evaluate the M_{max} for faults were based on empirical relationships between magnitude and surface-rupture length (SRL), rupture area (RA), and/or maximum displacement (MD) and average displacement (AD). M_{max} values ranged from M_w 5.7 to 6.8 for some of the linked systems. Earthquake recurrence rates for the faults were described using either recurrence intervals and/or SRs with most teams using the latter due to the lack of

Table 5. Summary of Seismic Source Characterizations for Ground Motion Hazard Assessment (Table 4-1 of CRWMS M&O 1998a)

Issue	AAR Team	ASM Team	DFS Team	RYA Team	SBK Team	SDO Team
TECTONIC MODELS						
Overall Approach	Viable models based on observations and inferred processes for the Crater Flat structural domain, with simple shear model given full weight (1.0). Superposed NW-SE dextral shear manifested as specific structures (tectonic models A, B, & C) (0.5) or not (tectonic model D) (0.5).	The source model incorporates various aspects of planar block fault (preferred), detachment, lateral shear, and volcanic-tectonic models.	Alternative tectonic and structural models are considered primarily in the characterization of local faults: domino model (0.8) (planar fault); detachment (0.2) (includes hypothetical hidden strike-slip fault of either local or regional extent).	None of the tectonic models presented provides a unified explanation for all the seismic, geologic, and geophysical data. Alternative tectonic and structural models are considered primarily in the characterization of local faults. A coalescing fault model best fits the Yucca Mountain area.	Preferred model: oblique rift-planar faults. Three-dimensional strain accommodated on planar, strike-slip, normal, and oblique-slip faults. Rock Valley and Highway 95 faults act as accommodation zones in the rift.	Alternative tectonic and structural models are considered in the characterization of local faults. Preferred model for Crater Flat – Yucca Mountain is a half-graben formed within a larger rift that opens and deepens to the north. Deformation history and structure are associated with carapace effect, clockwise vertical axis rotation, basaltic volcanism, age and behavior of Bare Mountain fault.
Planar Block-Faulting Models	Regional faults are modeled as independent and linked (for selected faults) planar faults to maximum seismogenic depth. Local faults include linked and coalesced models; planar faults to maximum seismogenic depth, to depth of local detachment, or in some cases to a depth constrained by allowable aspect ratio or by intersection with a higher-order fault.	Regional faults are modeled as independent planar faults to maximum seismogenic depth. Local faults—the preferred model is that the faults are planar to a depth controlled by the brittle-ductile transition and the Bare Mountain fault; treated as independent and coalescing faults that merge at depth.	Regional faults are modeled as independent planar faults to maximum seismogenic depth. Local faults—include models of independent (0.95) and distributed (0.05) fault behavior; alternative structural models (domino-planar and detachment-listric) used to constrain downdip geometry and extent.	Bare Mountain and regional faults are modeled as independent planar faults to maximum seismogenic depth. Local faults—planar to listric (1 to 3 coalescing systems).	Regional faults are modeled as independent planar faults to maximum seismogenic depth. Local faults—Yucca Mountain faults are part of a half-graben, with Bare Mountain as the master fault, predominantly normal slip with a left-lateral component.	Regional faults are modeled as independent planar faults to maximum seismogenic depth. Local faults: half-graben model (1) end member—all Yucca Mountain faults are seismogenic, continuous planar faults to maximum seismogenic depth. (2) carapace effect—only major block-bounding faults are through-the-crust seismogenic faults; other intrablock faults are confined to the carapace (i.e., are aseismic) or link to faults having different attitudes and aspect ratios below the unconformity.

Table 5 (Continued)

Issue	AAR Team	ASM Team	DFS Team	RYA Team	SBK Team	SDO Team
Shear Models (buried strike-slip faults or fault systems)	Included three alternatives: Model A – Throughgoing regional dextral shear zone (0.05); Model B - right-stepping dextral shear zone that produces a pull-apart basin WITHOUT an underlying cross-basin fault (0.6); and Model C - right-stepping dextral shear zone that produces a pull-apart basin WITH an underlying cross-basin fault (0.35).	Model 1 – Continuous, long (240-km) strike-slip fault zone as proposed by Schweikert considered. Regional (60-km-long) strike-slip fault given low weight. Model 2 – Shorter (25-km), more complex or segmented zone. Assessment of existence of buried strike-slip fault conditional on whether or not detachment exists; assessment of the seismogenic potential of the buried strike-slip fault is conditional on the depth of the detachment (shallow–0.8, moderate–0.6, deep–0.0).	Model allows for component of northwest-directed right-lateral strike-slip strain. Hypothetical hidden strike-slip fault source (probability of activity [P_a] = 0.05) is included in detachment model. Two postulated strike-slip fault sources are included: regional strike-slip fault (0.5) local strike-slip fault (0.5)	None (possibility of local buried source covered by background source).	A buried regional shear zone model is given low weight (0.01); no evidence for a buried strike-slip fault trending northwest across Crater Flat that would result in a earthquake larger than the maximum assigned to the host source zone.	Three sources of dextral shear were evaluated to account for vertical axis rotation at Yucca Mountain: (1) distributed shear (restricted to Crater Flat basin; basin is a discrete domain controlled by local bounding faults); (2) external transcurrent strike-slip fault (passes through the basin, totally hidden); and (3) external strike-slip fault enters basin from southeast (manifested at Yucca Mountain by the N25°W striking “hingeline”) and terminates in Crater Flat. Only (1) and (3) are credible modifications to the basic model.
Detachment Models	Regional detachment not viable (0.0), but hypothesized local detachments included, with weights dependent on the type of dextral shear structures assumed to be present. Local detachments not included as specific seismic sources; detachments affect only down-dip fault extent for local fault sources. Depths included for local detachments range from 3 km to the maximum thickness of the seismogenic crust, with 3 to 10 km preferred.	Detachment Model (0.15): Hypothesized detachment affects down-dip geometry and extent of local fault sources; seismogenic detachment is included as possible fault source with very low probability (see below).	Detachment Model (0.2): Hypothesized detachment chiefly affects down-dip geometry and extent of local fault sources; seismogenic detachment is included as possible fault source with very low probability (see below).	Detachments are not explicitly modeled. Possibility that local faults truncate down dip in a detachment or zone of decoupling is included in coalescing fault model.	Hypothesized detachment affects only the down-dip extent of local fault sources.	A seismogenic detachment (modeled as an independent source) was thoroughly considered but could not be substantiated by the available evidence.

Table 5 (Continued)

Issue	AAR Team	ASM Team	DFS Team	RYA Team	SBK Team	SDO Team
Volcanic-Tectonic Models ("ash event")	The possibility of simultaneous rupture on subparallel Yucca Mountain faults as postulated for the "ash event" is included in coalesced fault models for local faults.	The possibility that some surface rupturing earthquakes in Crater Flat are accompanied by dike injection (e.g., the 70-ka "ash event") is included in simultaneous rupture models for local faults.	The possibility of simultaneous rupture on subparallel Yucca Mountain faults as postulated for the "ash event" is included in the distributed faulting model for local faults.	The coalescing fault model used to model local faults (see below) would explain the apparent sychroneity of faulting on Yucca Mountain faults (i.e., the 70 ka "ash event").	Explicitly models a simultaneous rupture event (triggered by volcanic event; see Local Fault Model)	Distributed fault models involve simultaneous rupture of local faults that are parallel to each other. Such models would account for volcanism and tectonic faulting as a coupled process.
Thickness of Seismogenic Crust	Dmax1 11 km (0.185) 15 km (0.63) 17 km (0.185) Dmax2 14 km (0.185) 18 km (0.63) 22 km (0.185)	12 (0.1) 15 (0.6) 17 (0.3)	12 (0.6) 14 (0.3) 16 (0.1)	12 km (0.2) 15 km (0.7) 20 km (0.1)	12 (0.3) 15 (0.6) 17 (0.1)	14 km (0.2) 17 km (0.7) 19 km (0.1)
SEISMIC SOURCES						
Seismic Source Zones	Four scenarios: Scenario I w/3 zones (0.3), Scenario II w/2 zones (0.3), Scenario III w/3 zones (0.3), and Scenario IV w/1 zone (0.1). For all scenarios, a host zone (within 20-km radius) is defined only for assigning a lower M_{max}—not for separate recurrence estimate.	Two source zones within 100-km radius of site. A local zone (within 50-km radius) is included that is defined solely for assigning a lower M_{max}.	Model A (0.2) One zone Model B (0.8) Three zones Both models include a local zone that is defined for constraining M_{max} in the area of the detailed site characterization studies.	Three primary source zones within 100 km of site; two alternative configurations to model Zone A (local Yucca Mountain region) and Zone B (the zone surrounding Zone A).	Model A (0.7) 3 zones Model B (0.3) 4 zones Both models include a local zone that is defined solely for assigning a lower M_{max}.	Eight source zones within a 300-km radius of the site were considered initially, but only 3 remained given a filter of radius <100 km.
Seismic Source Zones—Recurrence	Truncated exponential recurrence model (1.0)	Truncated exponential recurrence model (1.0)	Truncated exponential recurrence model (1.0)	Truncated exponential recurrence model (1.0)	Truncated exponential recurrence model (1.0)	Truncated exponential recurrence model (1.0)
Seismicity Catalog	300-km radius catalog Version 7 (1.0) Adjustment made for underground nuclear explosions in relevant source zones.	300-km radius catalog Version 7 (0.7) Version 5 (0.3) Adjustment made for underground nuclear explosions.	300-km radius catalog Version 7 (0.5) Version 5 (0.5)	100-km radius catalog Version 5 (0.5) Version 7 (0.5)	100-km radius catalog Version 7 (0.3 to 0.6) Version 5 (0.4 to 0.7) Weights vary depending on source zone. In relevant zones, adjustments made for underground nuclear explosions weighted (0.4) versus no adjustment (0.6).	300-km radius catalog Version 5 (0.6) Version 7 (0.2) Version 8 (0.2)

Table 5 (Continued)

Issue	AAR Team	ASM Team	DFS Team	RYA Team	SBK Team	SDO Team
Spatial Smoothing Model	For Scenarios I - III: Uniform (1.0). For Scenario IV: h = 5 km (0.25) h = 10 km (0.5) h = 20 km (0.25)	Uniform (1.0)	Model A: h = 10 km (0.25) h = 25 km (0.6) Uniform (0.15) Model B: h = 10 km (0.22) h = 25 km (0.53) Uniform (0.25)	Uniform (0.4); h = 5 km (0.4) h = 15 km (0.2)	Uniform (1.0)	Uniform (0.5) h = 10 km (0.25) h = 20 km (0.25)
Seismic Source Zones—M_{max}	Excluding Host Zone 6.6 (0.3) 6.9 (0.4) 7.3 (0.3) Host Zone (within 20 km) 6.0 (0.3) 6.3 (0.4) 6.6 (0.3)	Walker Lane 6.5 (0.185) 6.8 (0.63) 7.1 (0.185) Basin and Range 6.9 (0.185) 7.2 (0.63) 7.5 (0.185) Site Region (within 50 km) 6.0 (0.185) 6.3 (0.63) 6.6 (0.185)	Model A (not including site vicinity) 7.0 (0.2) 7.3 (0.6) 7.7 (0.2) Model B (not including site vicinity) SW Walker Lane 7.0 (0.2) 7.3 (0.6) 7.7 (0.2) NE Walker Lane and Basin and Range 7.0 (0.2) 7.25 (0.6) 7.5 (0.2) Site Vicinity 5.6 (0.2) 5.8 (0.6) 6.0 (0.2)	6.0 (0.185) 6.3 (0.63) 6.6 (0.185)	Excluding Local Zone: 6.2 (0.2) 6.3 (0.5) 6.4 (0.2) 6.6 (0.1) Local Zone 5.6 (0.2) 6.0 (0.6) 6.2 (0.2)	Within 100 km 6.4 " 0.2 cumulative lognormal distribution 6.2 (0.03) 6.4 (0.5) 6.6 (0.97 Beyond 100 km: estimated from a correlation of fault length with magnitude for longest fault: in Zones 2 and 3 Ms 7.4 " 0.2
Regional Fault Sources	19 regional fault sources; includes faults with Pa of <1.0; includes two possibly linked fault systems: Death Valley with Furnace Creek (0.8), and Amargosa River with Pahrump (0.1); also includes five faults considered as segmented (max. rupture length < total fault length); included range of rupture lengths for each source. Preferred dips: normal 65° strike-slip 90°	24 regional faults (within 15 to 100 km of site); all fault sources active (1.0); considers alternative total lengths, generalized down-dip geometry (strike-slip 90°, normal 60°).	18 regional fault sources (within 100 km of site vicinity); all fault sources active (1.0); considered alternative total lengths, generalized down-dip geometry (strike-slip 90°, normal-60°).	11 regional fault sources (within 100 km of site); all fault sources active (1.0); includes possibility (0.1) of simultaneous rupture of Death Valley and Furnace Creek faults; includes alternative rupture lengths for 9 faults, generalized down-dip geometry (strike-slip 90°, normal 60°).	16 regional fault sources (within 100 km radius); includes faults with Pa < 1.0; includes range of rupture lengths for each source—for long faults ranges reflect probable rupture segment lengths, assigned dips based on fault type, with preferred values of: strike-slip 90°, normal 60°, and oblique 70°.	36 regional fault sources (24 faults (Pa 1.0), 12 faults (Pa < 1.0); two faults generally outside 100 km (Panamint Valley and Ash Hill fault zone) included; alternative total lengths, generalized down-dip geometry (strike-slip 90°, normal 60°).

Table 5 (Continued)

Issue	AAR Team	ASM Team	DFS Team	RYA Team	SBK Team	SDO Team
Regional Faults—M_{max}	SRL (0.4); RA (0.2); SRL and slip (0.4) M_{max} ± ¼ unit, M_{max} + ¼ = m^u	SRL (1.0) M_{max} ± ¼ unit, M_{max} + ¼ = m^u	SRL (1.0) Alternative rupture segments (SRL) are considered resulting in a range of M_{max} for each fault. M_{max} ± ¼ unit (with some exceptions)	SRL (0.35) RA (0.35) MD (0.3) or Rupture Length (RL) (0.5) RA (0.5) depending on available data M_{max} " 0.5 unit	SRL, RA, MD, AD, and moment approaches; weighted on a fault basis depending on available data. M_{max} ± ¼ unit, M_{max} + ¼ = m^u	RL, MD, RL x MD, SR +RL; weighted on a fault-specific basis depending on available data. M_{max} ± ¼ unit, M_{max} + ¼ = m^u
Regional Faults—Recurrence Approach	SR Approach (0.6); Recurrence Interval Approach (0.4) - where data are available. Characteristic (0.7) Modified exponential (0.3) DV –FC Characteristic (1.0) M_{max} + ¼ = m^u b-value 0.80 (0.3), 1.00 (0.4), 1.20 (0.3)	SR Approach (0.5) Recurrence Interval (0.5) or Slip Rate (1.0) depending on available data. Characteristic (0.2) Maximum moment (0.8) b-value varies from fault to fault.	SR Approach (1.0) Characteristic (0.6) Maximum moment (0.3) Truncated exponential(0.1) b-value varies from fault to fault.	SR Approach (1.0) Characteristic (0.9) Truncated exponential(0.1) b-value 1.07 (0.185) 1.12 (0.63) 1.2 (0.185) M_{min} = 6.3	SR and Recurrence Interval Approaches; weights vary from fault to fault depending on available data. Characteristic and truncated exponential models used. Weights vary from fault to fault, with characteristic behavior favored for range-bounding faults, and exponential for zones with multiple distributed traces. b-value varies from fault to fault.	Moment rates (SRs) Characteristic (0.7) Truncated exponential (0.3) b-value varies from fault to fault. M_{min} = 6.2
Local Fault Sources	20 individual faults included w/ probability of being seismic (P[s]) 0.1 to 1.0 Synchronous Behavior Approach: (1) Faults rupture independently or are grouped in distributed systems by linkages along strike or coalescence down dip. (2) Likelihood of coalesced behavior is dependent on tectonic model (in general, coalesced behavior strongly favored over independent behavior). (3) Four coalesced models defined with from one to four fault systems. Assigned weights depend on	Planar Fault Block Model- 5 faults modeled as major block-bounding faults (seismogenic–1.0) 5 faults modeled as minor or secondary faults (probability of being seismogenic—fault, P_A ranges from 0.5 to 0.9). Simultaneous rupture models are based on the probability of linkage at depth (geometric constraints) and temporal overlap inferred from paleoseismic data.	Two Fault Behavioral Models: Distributed (0.05) 9 scenarios Independent (0.95) Two Structural Models: *Domino* model (0.8) (high-angle planar faults to seismogenic depth except where they intersect larger-throw fault); existence of H95 fault not dependent on domino model—considered as an independent source with low probability of being an active seismogenic structure. *Detachment* model (0.2) listric geometry detachment modeled at 6 km depth; includes hidden strike-slip fault sources.	Coalescing Fault Model (1.0) Bare Mountain fault, independent planar fault to seismogenic depths. Yucca Mountain faults are assumed to coalesce down dip at relatively shallow depth (2 to 5 km). Windy Wash, Solitario Canyon, and Paintbrush Canyon faults are primary independent seismogenic faults in three-fault system. Coalescing Models: 12 km (0.2) and 15 km (0.7) seismogenic depth: 1-fault system (0.1) 2-fault system (0.5) 3-fault system (0.4) 20 km (0.1) seismogenic depth 1-fault system(0.3)	Within Crater Flat domain, included 11 individual faults (9 YM, BM, and Hwy 95); excluded 7 mapped faults based on no or low rates of Quaternary activity(P_A = 0) (including Ghost Dance and Sundance faults). Model- local faults sole into detachment between 5 km and base of seismogenic zone(0.01). Model- block-bounding faults coalesce at depth either in one or two master faults (0.09) Model (end member) - 4 linked block-bounding	Behavior models included: (1) single-fault (2) linked-fault (3) distributed-fault Single-fault scenarios - 6 major local faults 9 linked-fault scenarios 8 distributed fault scenarios

Table 5 (Continued)

Issue	AAR Team	ASM Team	DFS Team	RYA Team	SBK Team	SDO Team
	tectonic models, but models having three to four systems are strongly favored. (4) For independent fault behavior, two cases of possibly linked faults are generally favored. Preferred dip 60°. Dominantly normal slip w/ left-lateral component.			2-fault system(0.4) 3-fault system(0.3) Planar fault and detachment-decoupled model geometries are considered part of range of behavior for coalesced systems.	faults (0.4) Model (end member) - faults behave independently (0.5) All of the above models include a simultaneous rupture scenario that acts as an additional source; weights on activity vary according to rupture model (0.1 on independent and linked; 0.5 on detachment and coalescing models).	
Local Faults—M_{max}	Subsurface RL (for buried structures) or SRL (all others) RA SRL + slip Moment Equation Different weights assigned depending on fault length (< or ≥ 25 km), tectonic model, and coalesced behavior model. M_{max} ± ¼ unit, M_{max} + ¼ = m^u	General weights SRL (0.3) SRL x displacement(0.3) MD (0.15) AD (0.15) RA (0.1) Modified on a fault basis depending on available data. M_{max} ± ¼ unit, M_{max} + ¼ = m^u	RL (0.4) RA (0.6) ± 0.25 units	RL (0.5) RA (0.5) ± 0.5 units	SRL, RA, MD, AD, Seismic Moment inferred from stress drop; weights vary depending on available data. M_{max} ± ¼ unit, M_{max} + ¼ = m^u	RL (0.206) MD (0.104) RL x MD (0.207) RA (0.207) SRL + slip (0.069) Seismic Moment (0.207) M_{max} ± ¼ unit, M_{max} + ¼ = m^u

Table 5 (Continued)

Issue	AAR Team	ASM Team	DFS Team	RYA Team	SBK Team	SDO Team
Local Faults—Recurrence	SR Approach (0.6); Recurrence Interval Approach (0.4) - where data are available. Characteristic (0.7), Modified exponential (0.3) b-value: 0.80 (0.3) 1.00 (0.4) 1.20 (0.3)	SR Approach (0.5); Recurrence Interval Approach (0.5) Characteristic (0.7) Truncated Exponential (0.2) Maximum moment (0.1)	SR Approach (1.0) Independent behavior- Characteristic (0.6) Maximum moment(0.3) Exponential (0.1) Distributed behavior- Characteristic (0.6) Maximum moment(0.2) Exponential (0.2)	SR Approach (0.7) Recurrence Interval Approach (0.3) Characteristic and truncated exponential—weights vary depending on coalescing model used.	SR Approach (0.7 to 1.0) Recurrence Interval Approach (used where data are available, but given lower weight, 0.2 to 0.3) Both characteristic and truncated exponential models used (weight varies depending on fault model)	Moment Rate (0.33) Average Recurrence Interval (0.33) Interseismic Recurrence Interval (0.33) Characteristic (0.7) Truncated exponential (0.3)
OTHER SOURCES						
Buried Regional Dextral Shear Zone	Included w/ P[s] = 1.0 for Tectonic Model A (0.05). Regional strike-slip fault 50 to 100 km in length SR 0.05 (0.3) 0.1 (0.4) 0.2 (0.3)	Yes; see above. M_{MAX} M_w 7.1 (0.3) 60-km rupture M_w .6.7 (0.7) 25-km rupture SR 0.1 mm/yr (0.6) 0.025 mm/yr (0.2) 0.24 mm/yr (0.2)	Includes a hypothetical strike-slip fault of regional or local extent, with low probability (0.05) that it is a seismogenic source. Local strike-slip fault (0.5) 30-km length. Regional strike-slip fault (0.5) 200-km length.	Not included as fault source; possible buried strike-slip fault judged incapable of producing earthquakes larger than the maximum background earthquake or any other source included in the source model.	Not included as fault source; possibility is covered by seismic source zone.	Yes; see above. Fault Length 20 km (minimum) 27 km (preferred) 120 km (maximum) SR 0.001 (minimum) 0.005 (preferred) 0.02 (maximum)
Seismogenic Detachment (modeled as independent source)	No (possibility is covered by areal source zone).	Detachment Model (0.15) Probability—seismogenic (0.01) Depth to detachment 6 km (0.25) (BD-6) / 2- 6 km (0.5) BD (0.25) BD=brittle-ductile transition Maximum magnitude 7.1 (0.15) 7.6 (0.7) 8.0 (0.15) SR 0.05 mm/yr (0.6) 0.013 mm/yr (0.2) 0.12 mm/yr (0.2) Mean Recurrence 25 kyr (0.15)	Yes (Paintbrush Canyon /Stagecoach fault in the detachment model (0.2) is modeled as a shallow-dipping, seismogenic source that extends beneath the Crater Flat Basin).	Possibility of a seismic detachment is excluded.	No (shallow and deeper detachments as active seismogenic structures are given no weight). Hypothesized detachments affect only down-dip fault extent of Yucca Mountain faults; depth is dependent on Bare Mountain fault.	A seismogenic detachment (modeled as an independent source) was thoroughly considered but could not be substantiated by the available evidence.

Table 5 (Continued)

Issue	AAR Team	ASM Team	DFS Team	RYA Team	SBK Team	SDO Team
		75 kyr (0.7) 200 kyr (0.15) Characteristic(1.0)				
Volcanic Source Zone (basaltic)	No (possibility is covered by areal source zone).	No (maximum magnitudes for volcanic-related earthquakes are less than M_{max} for fault and background seismic zones, and recurrence rate for volcanic eruptive events is estimated to be insignificant compared to seismicity rates).	No (possibility is covered by seismic source zones).	Yes (0.7) Spatial location (basaltic cones in site vicinity). Preferred return periods 2×10^5 and 2×10^6 $M_{max} = 5.5$.	No (possibility is covered by seismic source zones).	Defines two volcanic sources with probabilities of 0.25 and 0.7. Recurrence—2 to 3 volcanic events per Ma Maximum magnitude distribution for volcanic events: 6.0 " 0.2 (0.1) 5.8 " 0.4 (0.6) 5.5 " 0.3 (0.3)
Gravity Fault	Considered distinct from Ash Meadows fault, which is included as a regional fault; accounted for in assessment of M_{max} for background source zones >20 km from site.	Not discussed. Ash Meadows fault is included as regional fault source (probability of activity 1.0).	Amargosa/Gravity (Ash Meadows) fault is included as regional fault source (probability of activity 1.0).	Not discussed. Ash Meadows fault included as regional fault.	Included as potential northern extension of the Ash Meadows fault (0.1).	Characterized as a regional fault source, probability of activity (0.9).
Cross-Basin Fault	Included w/ P[s] = 1 in Tectonic Model C (0.35)	Includes local buried strike-slip fault with low probability (see above); preferred length (25-km) (0.7) based on down-on-east segments along the west side of Crater Flat.	A local hidden strike-slip fault is included with a low probability (P_A = 0.05) in the detachment model for local faults.	Not explicitly included in SSC model; see comment above regarding buried strike-slip faults.	Not included.	Based on evidence for distributed dextral faulting, the hingeline-Pahrump-Stewart Valley fault is characterized as a buried strike-slip fault.
Highway 95 or Carrara Fault	Included w/: P[s] = 0.5 for Tectonic Model A P[s] = 0.8 for Tectonic Models B & C.	Carrara fault characterized as active (P_A = 0.85) regional fault source.	Included with low probability (P_A = 0.1) as a hypothetical regional source.	Not included.	Included as independent fault source (P_A = 0.4).	Highway 95 fault assigned a probability of 0.2 (regional fault source).

recurrence interval information. Preferred SRs ranged from about 0.001 mm/yr (Crater Flat faults) to 0.05 mm/yr (Stagecoach Road fault). Some of the linked faults were assigned slightly higher SRs. Four recurrence models were used depending on the teams' evaluations: characteristic, truncated exponential, modified truncated exponential, and maximum moment. Based on available displacement per event data, the characteristic recurrence model was favored by most teams for local fault sources.

In the characterization of local faults, alternative faulting behavior and structural models were evaluated by the SSFD expert teams to capture the range of complex rupture patterns and fault interactions. Based on extensive discussion and consideration of available geologic and geophysical data, a planar-fault block model was preferred by most teams; along-strike linkages or down-dip coalescence were interpreted by all teams. Simultaneous rupture of multiple faults was also included in all of the teams' interpretations. Five teams gave weight to detachment models with low probabilities to constrain the extent and geometry of the local faults, while others included the detachment itself as being seismogenic (Table 5).

Table 6. Fault Parameters of Significant Local Faults
Considered by SSFD Experts[1]

Fault Name	Rupture Length[2] (km)	Distance[3] (km)	Sense of Slip[4]	Fault Dip[2]	Slip Rate[2] (mm/yr)	Probability of Activity
Solitario Canyon	16-18.7	1	LL-N	50°-70°	0.01-0.03	1.0
Iron Ridge	6.5-8.5	2.5	LL-N	55°-70°	0.002-0.004	0.1-1.0
Bow Ridge	6.7-8	2.5	LL-N	60°-70°	0.002-0.003	0.4-1.0
Fatigue Wash	9.5-17	3.5	LL-N	55°-70°	0.002-0.009	0.9-1.0
Paintbrush Canyon	12-19.4	4	LL-N	50°-70°	0.002-0.017	1.0
Windy Wash	5-27	4.5	LL-N	55°-70°	0.003-0.03	0.6-1.0
North Crater Flat	6.5-13.3	6	LL-N	55°-60°	0.001-0.003	0.5-1.0
South Crater Flat	6.1-8.1	8	LL-N	60°-71°	0.001-0.008	0.5-1.0
Stagecoach Road	4.5-10	10	LL-N	50°-70°	0.016-0.05	1.0

Notes:

1 Only significant and potentially independent fault sources are included here; see Appendix E of CRWMS M&O (1998a) for complete discussion of all local fault sources including multiple fault rupture scenarios.

2 Range of preferred values interpreted by the expert teams

3 Approximate shortest distance to repository

4 LL = Left-lateral strike-slip; N = Normal slip

6.3.2.2 Regional Fault Specific Seismic Sources

Regional faults are those faults within about 100 km of Yucca Mountain that were interpreted as capable of generating earthquakes of M_w 5 or greater based primarily on fault length and histories of multiple Quaternary surface-rupturing earthquakes (Figure 6). These faults were evaluated and characterized by all SSFD expert teams using approaches similar to those used for characterizing local faults. However, overall characterizations of regional sources are less sensitive to and less dependent on alternative tectonic models. Paleoseismic data from Piety (1996) were used by all the teams to identify and characterize potential regional faults. Other sources, such as Anderson, Bucknam et al. (1995), Anderson, Crone et al. (1995), Keefer and Pezzopane (1996), McKague et al. (1996), and Pezzopane (1996) were also used by some of the teams. Some faults with probabilities of activity of only 0.1 and SRs less than 0.001 mm/yr were characterized by the experts. Some of the faults that McKague et al. (1996) considered active were not included as specific fault sources explicitly by the experts because of their short length, distance from Yucca Mountain, and evidence that many of these faults either have no significant Quaternary displacement or are much shorter than previously thought. However, these faults were implicitly considered by the experts as part of the areal source zones in their models.

The number of regional faults interpreted to be fault-specific seismic sources by the expert teams ranged from 11 to 36, reflecting the range of interpretations regarding regional fault activity. The specific seismic parameters of the most significant regional faults considered by most of the experts are shown in Table 7, whereas general parameters are described in Table 5 (under Regional Fault Sources). All teams modeled the regional faults as planar faults to maximum seismogenic depths primarily with dips depending on the style of faulting (preferred values of 90° for strike-slip faults, and generally 60° or 65° for normal-slip faults). The selection of maximum seismogenic depths relied on observations of contemporary seismicity including some of the better-studied large surface-faulting earthquakes in the Basin and Range province (e.g. 1983 Borah Peak earthquake). Alternative fault lengths were included to express uncertainty in their mapped lengths.

Of the regional faults, the most significant were the Furnace Creek and Death Valley faults because of their high SRs (2.5 to 8 mm/yr) and potential to generate large M_{max} of about M_w 7.5, despite their relatively long distances to the Yucca Mountain site ($\geq$ 50 km) (Figure 6).

Table 7. Fault Parameters of Significant Regional Faults
Considered by SSFD Experts

Fault Name	Rupture Length (km)[1]	Distance[2] (km)	Sense of Slip[3]	Slip Rate[1] (mm/yr)	Probability of Activity
Mine Mountain	20-23	11	LL-N	0.01-0.03	0.6-1.0
Bare Mountain	20-23	14	N	0.01-0.1	1.0
Wahmonie	14-15	22	N-LL	0.001-0.04	1.0
Ash Meadows	27-42	24	N	<0.01-0.04	1.0
Rock Valley	30-62.1	27	LL-N	0.02-0.16	1.0
Cane Spring	20-26	29	LL-N	0.01-0.03	0.6-1.0
West Specter Range	8-19	33	N	0.004-0.01	1.0
Amargosa River	12-24.8	34	N-RL	0.01-0.05	1.0
Yucca Lake	13-19	36	N-RL	0.005-0.2	0.5-1.0
Eleana Range	11-15	37	N	0.00024-0.2	1.0
Yucca Fault	25-32	40	RL-N	0.02-0.2	1.0
Keane Wonder	23-27	43	N	0.005	0.6-0.8
Furnace Creek	105-118	50	RL	4.0-8.0	1.0
West Springs Mountains	29-52	53	N	0.02-0.09	1.0
Death Valley	45-71	55	N-RL	2.5-5.0	1.0
Belted Range	21-50	55	N	0.01-0.1	1.0
Kawich Range	24-84	57	N	0.001-0.03	1.0
Pahrump	35-65	68	RL-N	0.005-0.07	1.0
West Pintwater Range	37-82	76	N	0.008-0.2	1.0

Source: CRWMS M&O 1998a, Appendix E

Notes:

1 Range of preferred values interpreted by the expert teams

2 Approximate shortest distance to repository

3 LL Left-lateral strike-slip, RL Right-lateral strike-slip, N Normal slip

The possibility that dextral (RL) shear is being accommodated in the Yucca Mountain region by a buried strike-slip fault was evaluated by all teams. Four teams included a regional buried strike-slip fault source with low probability. The other two teams gave zero weight to buried strike-slip fault sources. Although they did not preclude the possibility of a buried fault, they concluded that this source would be incapable of generating earthquakes larger than those associated with their regional source zones.

6.3.2.3 Areal Seismic Source Zones

For areal seismic source zones, the experts defined source boundaries based on seismotectonic province considerations, including the distribution of historical seismicity (Figure 1) and assessed M_{max} and recurrence. Some teams included alternative areal zone interpretations within 100 km of the site and defined zones beyond 100 km to completely express uncertainty in the seismic source interpretations. Several teams defined a background areal source zone representing the area near Yucca Mountain where detailed fault investigations have been conducted and, thus, where the mapping of faults is more complete. Table 5 summarizes key elements of the various models developed by each team for areal seismic source zones. An example map of part of one team's interpretations is shown on Figure 7. It shows the boundaries of various areal seismic source zones considered as one of four possible alternatives included in their characterization.

M_{max} distributions for the areal seismic source zones represent uncertainty in the largest background earthquake in the region (associated with the minimum threshold for surface faulting) and/or the estimated M_{max} for a geologic structure that was not explicitly included as a fault-specific seismic source. Earthquake recurrence for the areal seismic source zones was derived from the historical seismicity record. Four alternative historical earthquake catalogues were evaluated for completeness and dependent events (CRWMS M&O 1998a, Appendix G). Known fault-related earthquakes were removed and underground nuclear explosions and other forms of blasting and dependent events (e.g., foreshocks and aftershocks) were deleted using declustering algorithms (e.g., Youngs et al. 1987). Experts were required to consider the reservoir-induced seismicity associated with Lake Mead and aftershocks induced by nuclear explosions at the Nevada Test Site (Figure 1). Based primarily on their analyses of the historical seismicity catalog, all teams used the truncated exponential recurrence model to estimate earthquake recurrence rates within the areal seismic source zones (Table 5). Alternative interpretations of the background seismicity included (1) uniform smoothing of seismicity (uniformly distributed in space) and (2) nonuniform smoothing using different smoothing distances to account for an interpreted degree of spatial stationarity. The latter interpretation used the technique similar to that reported by Frankel (1995).

Seismicity related to volcanic processes, particularly basaltic volcanoes and dike-injection, was explicitly modeled in volcanic source zones by only two teams. Volcanic-related earthquakes were not modeled as a separate source by the other teams, who considered the low magnitude and frequency of volcanic-related seismicity accounted for by the areal source zones.

6.3.2.4 Combined Regional Recurrence

Earthquake recurrence (including both recurrence models and assigned rates of activity) is one of the most significant elements of seismic source characterization for PSHA because it greatly influences what contributes most to the hazard. Therefore, recurrence curves were one of the many aspects of the models examined by the experts during the feedback process for reasonableness and consistency. Figure 8 compares the aggregate (all teams combined) earthquake recurrence curves for all sources within 100 km of Yucca Mountain with each team's mean recurrence distributions (see Table 3 for team abbreviations). The range in uncertainty in the estimation of regional seismicity rates is generally less than an order of magnitude. At smaller magnitudes, the range reflects the differences in the teams characterization of the regional source seismic zones. The overprediction of the observed rate of M_w 4 to 5 earthquakes within 100 km of the site reflects the teams' general assessment that larger regions are needed to characterize the seismicity rates. At larger magnitudes, the assessments from the individual teams lie within the uncertainty in the occurrence rates of earthquakes based on the historical record.

6.3.3 Ground Motion Attenuation Characterization

The physical characteristics of strong ground motion that potentially contribute to damage are amplitude, frequency, and duration. In general, larger-magnitude earthquakes generate larger-amplitude motions for longer time periods, which in turn cause greater damage. Additionally, larger-magnitude events generally cause larger long period motions. However, predicting strong ground motions is complex because ground motion characteristics depend on other factors in addition to earthquake magnitude. These can be grouped into source, path, and site factors. Source factors not only include earthquake size, but also encompass type of faulting (normal, strike-slip, or reverse), and other dynamic properties of the fault rupture as it breaks through the earth. Path factors include the distance, geologic structure, and crustal material properties between the earthquake source and site. Finally, site effects include the local conditions such as structural geology, types of surficial deposits, depth to the water table, and topography.

Numerous empirical attenuation relations that estimate ground motion amplitudes have been developed from strong motion records of historical earthquakes. The ground motion amplitudes can be expressed using a variety of measures, including PGAs, PGVs, and SAs. These different measures are used to characterize different frequencies and types of motions. Ground motion is most often measured in terms of PGA, which is typically expressed in units of "g," a percent of standard gravity (9.8 m/s^2). PGAs characterize high frequency ground motions (defined as 100 Hz for the Yucca Mountain PSHA), whereas PGVs (usually measured in cm/sec) characterize lower frequency or longer period motions. SAs are used to measure the frequency dependence of the response of structures to ground motions and are calculated for a variety of frequencies (0.3, 0.5, 1, 2, 5, 10, and 20 Hz for the Yucca Mountain PSHA). The attenuation relations for estimating ground motions incorporate the effects of the more significant factors such as magnitude, distance, faulting mechanism, crustal attenuation, and type of deposits at the site. Unfortunately, strong motion data are limited for the conditions directly applicable to Yucca Mountain, presenting many challenges to the GM experts that are discussed further below.

Due to differences in seismicity rates, stress regimes, and attenuation parameters, strong motion data from the Basin and Range province, even when combined with the very limited data from analog tectonic environments, are insufficient to adequately constrain empirical attenuation models. Consequently, a key issue with respect to characterizing ground motion attenuation in the Yucca Mountain region was the applicability of western U.S. attenuation models that are based on relatively large data sets, to the Basin and Range province. Most empirical attenuation relations in the western U.S. are based on recordings from California strike-slip and reverse-slip earthquakes. Due to the sparse strong motion data recorded from normal faulting earthquakes, separate style-of-faulting factors typically have not been estimated for normal dip-slip faulting. Instead, the normal faulting data are usually grouped with strike-slip faulting data. Preliminary analyses of the few normal faulting strong ground motion recordings have been found to not be statistically different from those predicted for strike-slip faulting in previous evaluations (Westaway and Smith 1989). However, subsequent studies of an expanded dataset indicate that various differences exist between records from extensional and compressional regimes (e.g., Spudich et al. 1996).

In their evaluations, the GM experts considered the possibility that significant differences may exist in the seismic source, regional crustal path, and shallow site properties for Yucca Mountain as compared to average source, path, and site properties represented in the western U.S. strong motion data set. An issue that the GM experts addressed was whether, or to what degree, any such differences affect median ground motion estimates or variability in ground motions expected at Yucca Mountain compared to those predicted by western U. S. empirical ground motion models based primarily on California data.

6.3.3.1 Specific Ground Motion Issues

In addition to the general issue of evaluating the applicability of empirical strong motion models based largely on strong motion data recorded in California, several specific issues were identified by the GM experts and prioritized as to importance for further study. Most arose from a lack of detailed information or from a need to further evaluate an available data set. A discussion of three key issues, site response, stress drops for normal faulting earthquakes and numerical simulations, follows. For a more complete discussion of all issues considered by the GM experts see Appendix F of CRWMS M&O (1998a).

6.3.3.1.1 Site Response

The ground motion hazard assessment was for a site located on "typical" emplacement-level tuff at Yucca Mountain (near Point 8 on Figure 3). To develop ground motions for this site condition, the GM experts required detailed information on the shear-wave velocity and nonlinear properties of the shallow tuff at Yucca Mountain (primarily the top 50 m). A preliminary velocity profile for the shallow tuff had been estimated as part of a scenario earthquake modeling project (Schneider et al. 1996), but this velocity profile was not well constrained. The available laboratory testing studies to determine the nonlinear properties were not adequate to meet the experts' needs. Thus, the GM experts requested that additional studies to evaluate the shear-wave velocity and nonlinear properties of the shallow tuff be conducted. Although limited additional studies were performed, they did not adequately define the site properties to the extent required for site-specific application. Therefore, it was decided to define a reference site condition by removing the top 300 m from the shear-wave velocity profile used in the scenario earthquake modeling project. This site condition was called the reference rock outcrop (represented by Point A on Figure 4). The mean shear-wave velocity for the reference rock at a 300-m depth is 1,900 m/sec.

The parameter kappa is a measure of the near-surface attenuation of seismic waves. Analyses of California sites yield kappa values of approximately 0.04. In order to accurately predict high-frequency ground motions at Yucca Mountain, a local estimate of kappa must be obtained. To define the appropriate kappa beneath the reference rock outcrop, kappa was determined for the upper 300 m and subtracted from the average kappa at the surface. The average kappa for sites at the surface at Yucca Mountain was previously estimated to be 0.02 sec based on studies by Su et al. (1996). Laboratory studies of the low-strain damping of the tuff in the top 300 m (Stokoe et al. 1998) revealed very low values with an equivalent kappa of 0.0014 sec in the top 300 m. Therefore, subtracting 0.0014 sec from 0.02 sec resulted in a median kappa of 0.0186 sec for the reference rock outcrop (CRWMS M&O 1998a, Section 5). It is expected that kappa will vary over the site area due to variations in rock properties and this variability was accounted for by the GM experts in their estimates of uncertainty in their ground motion attenuation relationships.

The reference rock outcrop provided a better defined reference site condition for the experts to estimate their ground motions. With the change of the reference site condition from the surface of the tuff (represented by Point C on Figure 4) to the reference rock outcrop (represented by Point A), the nonlinear properties of the tuff were not needed for the development of ground motions in this study. However, nonlinearity of the tuff is discussed in Section 5.7 of CRWMS M&O (1998a) and will be addressed in future computations of the seismic design ground motions for the repository.

6.3.3.1.2 Stress Drops for Normal Faulting Earthquakes

Spudich et al. (1996) found lower ground motions for earthquakes in extensional regimes than for earthquakes in transpressional regimes. Since their analysis was based on residuals from attenuation relations, it was not clear whether this difference was due to earthquake source, path, or local site effects. The GM experts requested computations of stress drops for the Spudich et al. (1996) data set to compare with stress drops for California earthquakes to help determine the causes of the ground motion differences.

Median stress drops for extensional tectonic environments were computed using the normal-faulting earthquakes in the Spudich et al. (1996) worldwide data set. The stress drops were found to be consistently lower than those for California earthquakes (Becker and Abrahamson 1997). To adjust for this difference in stress drop, ground motion scale factors were developed. See CRWMS M&O (1998a), Sections 5.3.1 and 5.4.1, for further discussion of the stress drop analysis.

6.3.3.1.3 Numerical Simulations

Numerical simulations of ground motions at Yucca Mountain were available for the earthquakes considered in the scenario earthquake modeling project (Schneider et al. 1996). The experts, however, were required to estimate the ground motions for a much larger range of magnitudes and distances than was considered in that study. Therefore, the GM experts requested that numerical simulations be generated for the full set of events (point estimates) that were considered for the PSHA. Three preferred methodologies were identified by the experts from the six included in the scenario earthquake modeling project. The procedures by: (1) Zeng and Anderson; (2) Silva; and (3) Somerville were selected based on their perceived superior modeling ability as evidenced by comparisons included in the scenario earthquake modeling project (Schneider et al. 1996). Ground motions for the required point estimates were then generated for the reference rock outcrop.

6.3.3.2 Ground Motion Experts' Evaluations

Ground motion evaluations were performed using an expert elicitation process similar to that used for seismic source and fault displacement characterization. The evaluations developed by each expert are described in Appendix F of CRWMS M&O (1998a). The elicitation process was facilitated by the GM Facilitation Team and included three workshops, two working meetings, and a 1-day elicitation meeting with each GM expert (Figure 2).

The seven GM experts estimated median ground motion, aleatory variability, and epistemic uncertainties for a matrix of earthquake magnitudes, source-to-site distances, and faulting styles (normal- and strike-slip) and for a suite of spectral frequencies (CRWMS M&O 1998a, Section 5). The ground motions were defined at the reference rock outcrop. These estimates were based on empirical and numerical simulation-based models and combinations of conversion factors. The experts classified proponent models as empirical attenuation relations, hybrid empirical, point-source numerical simulation, finite-fault numerical simulations, and blast models. A complete list of the models is shown in Table 8, and the models are described in Section 5 of CRWMS M&O (1998a).

As discussed above, a fundamental issue that the experts evaluated is whether ground motions at Yucca Mountain differ significantly from the motions represented by the data set that forms the basis for western U.S. empirical models and, if they differ, by how much. Differences could be caused by source, path, or site effects. The region- and site-specific aspects of the ground motion could be directly incorporated as input for the numerical simulations, but for the empirically based models, proponent conversion factors were developed to account for these differences. Suites of conversion factors were obtained using the results of (1) numerical finite-fault simulations, (2) stochastic point-source simulations, and (3) empirical attenuation relations. The conversion factors included corrections for:

- Source -- western U.S. sources to Yucca Mountain extensional sources
- Crust -- western U.S. crust to Yucca Mountain crust
- Site -- Yucca Mountain surface to reference rock outcrop

Due to the large number of estimates required, the experts used numerical weighting of proponent model estimates to develop their initial estimates. The procedure applied two levels of weights. The models were first separated into classes or types as shown in Table 8. Weights were then assigned based on the expert's evaluation of the applicability of each class. Then for each range of magnitude, distance, and fault type, weights were assigned to the models, within each class, based on the expert's evaluation of the strengths and weaknesses of each model in

Table 8. Proponent Ground Motion Models Used by Each Expert

Model Class	Proponent Models in Class	Anderson	Boore	Campbell	McGarr	Silva	Somerville	Walck
Empirical	Abrahamson and Silva (1997)	Yes	Yes	Yes[1]	Yes	Yes	Yes	Yes
	Boore et al. (1997) (Vs model)	Yes	Yes	Yes[1]	Yes	Yes	No	Yes
	Campbell (1997) (Soft Rock)	Yes	Yes	Yes[1]	Yes	Yes	Yes	Yes
	Idriss (University of California, Davis, written communication, 1997) (Rock, Stiff Soil) (PSHA)[2]	Yes	Yes	Yes[1]	Yes	No	Yes	Yes
	Joyner and Boore (1988) (Rock)	No	Yes	Yes[1]	Yes	Yes	Yes	Yes
	McGarr (1984) (Rock)	No	Yes	No	Yes	No	No	Yes
	Sadigh et al. (1997) (Rock)	Yes	Yes	Yes[1]	Yes	Yes	Yes	Yes
	Sabetta and Pugliese (1996) (Rock)	Yes	No	No	No	No	No	Yes
	Spudich et al. (1996) (Rock)	Yes	Yes	Yes[1]	Yes	No	Yes	Yes
Hybrid Empirical	Campbell (PSHA)[2]	No	No	Yes	No	No	No	No
Finite Fault Simulation	Silva Case A (PSHA)[2]	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Silva Case B (PSHA)[2]	No	No	No	No	No	No	No
	Somerville (PSHA)[2]	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Zeng and Anderson Case A (PSHA)[2]	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Zeng and Anderson Case B (PSHA)[2]	Yes	No	No	No	No	No	No
	Zeng and Anderson Case C (PSHA)[2]	Yes	No	No	No	No	No	No
Point Source Random Vibration Theory	Silva (PSHA)[2]	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Blast	Bennett Model 2 (1995 Scenario Study) (PSHA)[2]	No	No	No	No	No	Yes	Yes

Note:

[1] These empirical models are incorporated in the Hybrid Empirical model.
[2] PSHA = CRWMS M&O (1998a).

terms of its applicability to Yucca Mountain. In general, each expert varied the class and model weights on a case-by-case basis to reflect his/her assessment of the applicability of each model. For example, an expert may have downweighted or eliminated an empirical model outside the magnitude range represented by the data on which the empirical model was based. The resulting matrix of point estimates consisted of 51 combinations of parameters that were considered to adequately define attenuation for the seismic sources addressed by the SSFD expert teams. The matrix covered a range of conditions, including: M_w 5.0 to 8.0, distances from 1 to 160 km, and strike-slip and normal-slip faulting (for both the hanging wall and footwall). The range of frequencies, for which ground motion was evaluated, was selected to span the range of interest for the proposed Yucca Mountain SSCs: 0.3, 0.5, 1, 2, 5, 10, and 20 Hz in addition to PGA and PGV. The GM experts also evaluated two special cases: multiple parallel fault rupture and a shallow detachment fault because the SSFD experts had included these cases in their seismic source characterizations. Scaling rules were developed to apply to their models in order to represent these seismic sources (CRWMS M&O 1998a).

The experts used logic trees to characterize uncertainty in their ground motion evaluations. In a typical logic tree, alternative models make up the branches of the tree. A model consists of both the median ground motion and the aleatory variability (standard deviation). The expert-to-expert differences in the median ground motions and in the standard deviations of the alternative models constitute the epistemic uncertainty. Each GM expert evaluated the alternative models individually and developed his/her own composite model for their best estimates of the median and standard deviation for a given earthquake magnitude and source-site geometry (distance). In addition, each quantified the epistemic uncertainty associated with their estimates of the median and standard deviation. Thus, the expert's ground motion estimates consisted of four values: median, aleatory standard deviation, epistemic uncertainty about the median, and epistemic uncertainty in the aleatory variability. By providing his/her estimates of the epistemic uncertainty, each expert provided the effects of his/her own logic trees on the ground motion attenuation. Thus, the use of seven experts provided alternative logic trees, not just alternative ground motion models.

Each GM expert's point estimates of the ground motion were regressed by the GM Facilitation Team to develop Yucca Mountain attenuation equations for use in the hazard calculations. Each GM expert defined the distance measure used in the regression analyses for his/her point estimates. Each expert evaluated whether the footwall and hanging wall point estimates were regressed together, as a single normal faulting attenuation equation, or separately, yielding separate models for sites on the hanging wall and footwall. In addition, the experts evaluated the degree of magnitude saturation at close distances.

As an example, the median PGA attenuation for the hanging wall of a M_w 6.5 normal faulting earthquake is shown on Figure 9a and the epistemic uncertainty about the median is shown on Figure 9b. The total epistemic uncertainty for the median ground motion is a combination of the range of the expert's estimates of the median (range on Figure 9a) and the uncertainty associated with each expert's estimate (Figure 9b). Note that if the median ground motion estimates are very similar, it does not mean that no epistemic uncertainty exists; that would be the case only if the epistemic uncertainty was zero. Similar plots for the best estimate of the standard deviation and epistemic uncertainty in the standard deviation are shown on Figures 9c and 9d. Consensus on the median values occurs when the expert's estimates of the median and standard deviation are within each epistemic uncertainty of the others. Significant differences occur when the experts' median estimates differ by more than the epistemic uncertainty.

6.3.4 Fault Displacement Characterization

The SSFD expert teams developed original approaches and methodologies to characterize fault displacement potential for input to the fault displacement hazard assessment (CRWMS M&O 1998a). The approaches were based primarily on empirical observations of faulting characteristics at Yucca Mountain and in the Basin and Range province during past earthquakes (both historic and prehistoric). Empirical data were fit by statistical methods to quantify faulting parameters and their variability. These results were then used by the teams to develop their approaches and characterize the fault displacement potential at the nine demonstration sites, including the uncertainty.

Approaches to characterizing fault displacement potential were developed to be applicable to any location within the proposed repository area. To demonstrate the application of these evaluations and to provide an estimate of the fault displacement hazard, nine demonstration points were selected (see Figure 3) for fault displacement hazard characterization. Selected points represent the expected range of fault displacement hazard conditions within the site area in terms of the types of features that may be encountered and include: potentially seismogenic block-bounding faults with greater than 50 m of cumulative offset, north- and northwest-striking mapped intrablock faults that have a few to tens of meters of cumulative displacement, and additional features observed within the ESF that are likely to be encountered within the proposed repository block. These features range from small faults uncorrelated with a mapped surface feature to intact rock. The selected points are (Figure 3):

Point 1 -- A location on the Bow Ridge fault where it crosses the ESF. The Bow Ridge fault is a block-bounding fault that has been characterized by the SSFD expert teams as being a potentially seismogenic fault and/or to be part of a seismogenic fault system.

Point 2 -- A location on the block-bounding Solitario Canyon fault, which has been characterized by the expert teams as one of the longer seismogenic faults within the Yucca Mountain site vicinity.

Point 3 -- A location on the Drill Hole Wash fault where it crosses the ESF. The Drill Hole Wash fault is one of the longer of the northwest-striking faults within the Yucca Mountain site vicinity.

Point 4 -- A location on the Ghost Dance fault, which is one of the longer north-south intrablock faults within the site area.

Point 5 -- A location on the Sundance fault within the proposed repository footprint west of the ESF. The Sundance fault is an intermediate length, northwest-trending intrablock fault.

Point 6 -- A location on a small fault mapped in bedrock on the west side of Dune Wash. This point represents a location on one of the many small north-south-striking intrablock faults mapped at the surface of Yucca Mountain.

Point 7 -- A location approximately 100 m east of Solitario Canyon at the edge of the proposed repository footprint. Any one of four hypothetical conditions were assumed to exist at this location. The conditions represent features that were encountered within the ESF but are not directly correlated with specific features observed at the surface:

(a) A small fault having 2 m of cumulative displacement

(b) A shear having 10 cm of cumulative displacement

(c) A fracture having no measurable cumulative displacement

(d) Intact rock

Point 8 -- A location within the proposed repository footprint midway between the Solitario Canyon and Ghost Dance faults. The same four hypothetical conditions were assumed to exist here as at Point 7.

Point 9 -- A location in Midway Valley east of the Bow Ridge fault on an observed fracture having no measurable displacement in Quaternary alluvium.

The potential for fault displacement was categorized as either principal or distributed faulting, both of which are potential hazards to SSCs. Principal faulting occurs along a main plane (or planes) that is the locus for release of seismic energy. Where the principal fault rupture extends to the surface, it may be represented by displacement along a single narrow trace or over a zone that is a few to many meters wide. Distributed faulting is rupture that occurs on faults in the vicinity of the principal rupture in response to the principal displacement. Distributed faulting is spatially discontinuous and may occur over a distance of several tens of meters to many kilometers from the principal rupture. A fault that can produce principal rupture may also undergo distributed faulting in response to principal rupture on other faults.

The basic formulation of the probabilistic hazard model for fault displacement is analogous to that for computing ground-shaking hazard (compare Sections 6.5.1. and 6.6.1). The hazard can be represented probabilistically by a displacement hazard curve that is analogous to a ground motion hazard curve. The curve depicts annual occurrence of fault displacement values (i.e., the annual frequency of exceeding a specified amount of displacement). Thus, the hazard curve is a plot of the frequency of exceeding fault displacement value d, designated by $v(d)$. This frequency can be computed using the expression:

$$v(d) = \lambda_{DE} P(D > d) \qquad \text{(Eq. 6-1)}$$

where λ_{DE} is the frequency of displacement events at a point of interest, and $P(D > d)$ is the conditional probability that the displacement D in a single event will exceed value d.

Several approaches were developed by the SSFD expert teams to characterize λ_{DE} and $P(D > d)$. Approaches to characterize λ_{DE} can be divided into two categories: the displacement approach and the earthquake approach. The displacement approach provides an estimate of the frequency of displacement events directly from feature-specific or point-specific observed displacements. The earthquake approach relates the frequency of displacement events to the frequency of earthquakes generated by the seismic source using the seismic source characterization input to the ground motion hazard assessment.

For principal faulting, the conditional probability of exceedance, *P(D > d),* contains two-parts: the variability of slip from event to event, and the variability of slip along strike during a single event. The teams developed several approaches for characterizing the distribution of slip at a location given a principal faulting event.

6.3.4.1 Team Approaches and Characterizations of Fault Displacement Potential

The approaches and characterization of fault displacement potential at the nine demonstration points are described in detail in Appendix E of CRWMS M&O (1998a), for each team. Table 9 is from Section 4.3.2.1 of CRWMS M&O (1998a) and it summarizes key points of the fault displacement characterizations, for each team. The following section provides a general discussion of some of these key points. For more detail see also Section 4.3.2.1 of CRWMS M&O (1998a).

In aggregate, the six SSFD expert teams slightly preferred the displacement approach (aggregate weight ~ 0.6) over the earthquake approach for characterizing fault displacement potential at sites subject to principal faulting and at sites subject to only distributed faulting. For characterizing principal faults, four of the teams used only one approach (Table 9). Three teams used only one approach for characterizing displacement potential on distributed faults.

Principal faulting hazard was assessed for sites located on faults that the SSFD expert teams identified as being seismogenic. In the displacement approach, the preferred method for estimating λ_{DE} used SR divided by the AD per event. The expert teams used a number of approaches to evaluate *P(D>d),* based on empirical distributions derived from Yucca Mountain trenching data. These distributions were normalized by various parameters, including the expected MD in the maximum event, the AD estimated from displacement data, and the AD and MD estimated from the length of the fault.

To characterize λ_{DE} for assessing displacement hazard on principal faults using the earthquake approach, the teams used the frequency of earthquakes they had evaluated for the ground motion hazard assessment and multiplied it by the conditional probability that an earthquake produces surface rupture at the site of interest. The along-strike intersection probability was computed using the rupture length estimated from the magnitude of an event randomly located along the fault length. Most teams used an empirical model based on historical ruptures to compute the probability of surface rupture. The preferred approach to assess *P(D>d)* was to define a distribution for the MD based either on the magnitude or the rupture length of the earthquake. This distribution was convolved with a distribution for the ratio of the displacement to the MD to compute *P(D>d).*

The preferred approach to characterize λ_{DE} on features subject to only distributed faulting used SR divided by the AD per event (displacement approach). The SRs were derived using the cumulative displacement and slip history on the fault or feature. The teams used approaches for evaluating *P(D>d)* similar to those used in the displacement approach. The empirical distributions were combined with a scaling relationship, used to estimate the AD per event, to obtain *P(D>d)*.

Table 9. Summary of SSFD Expert Team Fault Displacement Hazard Characterizations (Table 4-3 of CRWMS M&O 1998)

Issue	AAR Team	ASM Team	DFS team	RYA Team	SBK Team	SDO Team
PRINCIPAL FAULTING APPROACH	Displacement approach [0.67]; Earthquake approach [0.33]	Earthquake approach [1.0]	Displacement approach [1.0]	Displacement approach [1.0]	Displacement approach [0.85-0.9] Earthquake approach [0.1-0.15]	Earthquake approach [1.0]
			Displacement Approach for Principal Faulting			
Probability That Principal Faulting Can Occur P(C)	Evaluate P(C) based on probability fault is seismogenic	NA	Evaluate P(C) based on probability fault is seismogenic	Evaluate P(C) based on probability fault is seismogenic	Evaluate P(C) based on probability fault is seismogenic	Evaluate P(C) based on probability fault is seismogenic
Frequency of Displacement Events	SR [1.0]	NA	$SR/\overline{D}_E$ [0.5]; Recurrence intervals (*RI*) [0.5]	SR [0.2]; Recurrence intervals [0.8]	SR [0.8]; Recurrence intervals [0.2]	NA
SR	Quaternary slip rates used in SSC model	NA	Paleoseismic data [0.7]; Uniform post-Tiva Canyon [0.1]; Uniform post-Rainier Mesa [0.1]; Decreasing slip rate model [0.1]	Quaternary slip rates used in SSC model	Quaternary paleoseismic data point specific or interpolated	NA
AD Per Event, $\overline{D}_E$	$\overline{D}_E = 0.83\ MD^{max}$ (MD^{max} from: fault length [0.3]; D_{cum} [0.3]; and, paleoseismicity data [0.4])	NA	Paleoseismic data [0.5]; $SR \times RI$ [0.5]	Paleoseismic data [1.0]	Paleoseismic data [0.8]; From *AD-RL* [0.1]; From *MD-RL* [0.1];	NA
Conditional Probability of Exceedance, *P(D>d)*	Distribution for D/MD^{max} [1.0]	NA	Distribution for *D/AD* [1.0]	Distribution for *D/AD* [0.5]; Distribution for D/MD^{max} [0.5]	D/AD_{paleo} $D/AD_{F(RL)}$ $D/MD_{F(RL)}$ correlated with $\overline{D}_E$	NA
			Earthquake Approach for Principal Faulting			
Probability That Principal Faulting Can Occur, P(C)	P(C) = P(S) from source model for GM assessment	P(C) = P(S) from source model for GM assessment	NA	NA	P(C) = P(S) from source model for GM assessment	P(C) = P(S) from source model for GM assessment
Frequency of Earthquakes on Principal Faulting Source	Earthquake frequency from source model for GM assessment	Earthquake frequency from source model for GM assessment	NA	NA	Earthquake frequency from source model for GM assessment	Earthquake frequency from source model for GM assessment

Table 9 (Continued)

Issue	AAR Team	ASM Team	DFS team	RYA Team	SBK Team	SDO Team
Probability of Surface Rupture	Randomization of rupture depth with rupture width based on *RL/*aspect ratio; *RL* specified by magnitude-*RL* [0.5]; magnitude-rupture area [0.5]	Empirical models 32 Great Basin earthquakes [0.5]; 105 Worldwide earthquakes [0.5]	NA	NA	Empirical model 32 Great Basin earthquakes [1.0]	Empirical models 32 Great Basin earthquakes [0.5]; 47 Northern Basin and Range earthquakes [0.5]
Conditional Probability of Exceedance, *P(D>d)*	Maximum displacement per event, *MD*, from *SRL* [0.33]; M_w [0.33]; and *RLD* [0.34]; *D/MD* from Wheeler data [1.0]	*MD* from M_w [1.0] *D/MD* from Wheeler data [1.0]	NA	NA	*MD* from M_w [1.0] *D/MD* from Wheeler data [0.5]; fractal model [0.5]	*AD* and distribution for *D/AD* [0.5]; *(AD* from*: M_w [0.2]; *RL* [0.4]; and Paleoseismic data [0.4]) *MD* and distribution for *D/MD* [0.5]; *(MD* from*: M_w [0.2]; *RL* [0.4]; and Paleoseismic data [0.4];) *D/MD* from: Wheeler data [0.8], fractal model [0.2] * for $m<m^U$-½ use only M_w Ramelli curve, also was used for Solitario Canyon fault

Table 9 (Continued)

Issue	AAR Team	ASM Team	DFS team	RYA Team	SBK Team	SDO Team
DISTRIBUTED FAULTING APPROACH	Displacement approach [0.67]; Earthquake approach [0.33]	Earthquake approach [1.0]	Displacement approach [1.0]	Displacement approach [1.0]	Displacement approach [0.8]; Earthquake approach [0.2]	*On Principal Faults*– Earthquake approach [1.0]; *Other Sites*– Displacement approach [0.3, Earthquake approach [0.7]
Earthquake Approach for Distributed Faulting						
Probability of Occurrence P(C)	If capable of principal faulting P(C) = P(S) Otherwise, P(C) based on slip-tendency	Function of the category and orientation of feature, cos(strike azimuth)	NA	NA	P(C)=1.0	Slip tendency [1.0]
Frequency of Earthquakes on Seismic Sources	Earthquake frequency from SSC model	Earthquake frequency from SSC model	NA	NA	Earthquake frequency from SSC model	Earthquake frequency from SSC model
Probability of Slip Per Event, P_i(Slip|Event on j)	Logistic regression of historical faulting data [1.0]	Probability a function of r and hanging wall-footwall location; preferred model [0.6]; upper-bound model [0.4]	NA	NA	$P(\theta) \times F(event)$ $P(\theta)$ based on slip tendency [0.5]; Relative orientation [0.5] *F(event)* based on logistic regression of historical surface faulting data [0.5], peak velocity [0.5]	$P(\theta) \times F(event)$ $P(\theta)$ based on relative orientation [1.0] *F(event)* based on logistic regression of historical surface faulting data [1.0]

Table 9 (Continued)

Issue	AAR Team	ASM Team	DFS team	RYA Team	SBK Team	SDO Team
Conditional Probability of Exceedance, *P(D>d)*	*For site of principal faulting* use principal faulting–distribution times a reduction factor (*RF)* [1.0] *For other sites*– Distribution of D/MD^{max}; (MD^{max} from: *RL* [0.5], D_{cum} [0.5])	*RF* times principal faulting distribution; (*RF* from: Displacement potential [0.7], Relative cumulative displacement [0.3])	NA	NA	D/D_{cum} [1.0]	Distribution for *D/MD* on principal rupture as a function of distance from rupture [0.8], Distribution for *D/MD* on principal rupture times function of relative D_{cum} [0.2]
Displacement Approach for Distributed Faulting						
P(C)	Evaluate P(C) based on orientation.	NA	Evaluate P(C) based on orientation, location, and P(S)	Evaluate P(C) based on orientation, location, and P(S)	P(C)=1.0	Based on slip tendency [1.0]
Frequency of Distributed Faulting Events	Slip rate [1.0]	NA	$SR/\overline{D}_E$ [0.5], and Recurrence intervals (*RI*) [0.5]	Slip rate [1.0]	Slip rate [1.0]	Slip rate [1.0]
SR	Uniform post 11.6 Ma [0.1], Uniform post 3.7 Ma [0.3], and 3.26×10^{-5} D_{cum} [0.6]	NA	Uniform post-Tiva Canyon [0.33], Uniform post-Rainier Mesa [0.33], and Decreasing slip rate model [0.34]	D_{cum}/12.7 [0.1], 0.02 D_{cum}/1.6 [0.6], and 0.2 D_{cum}/3.7 [0.3]	Geologic history [0.75] (with: D_{cum}/12.5 [0.1], 0.2 D_{cum}//11.6 [0.3], and 0.8 D_{cum} x 0.21/0.9 [0.6]) Ratio of cumulative slip to that of block-bounding faults and their slip rates [0.25]	0.02 D_{cum}/1.6Ma [0.3]; 0.006 D_{cum}/1.6Ma [0.4]; 0.002 D_{cum}//1.6Ma [0.3]
AD Per Event, $\overline{D}_E$	0.83MD^{max} from Length [0.5], D_{cum} [0.5]	NA	Direct estimate [0.5] SR*RI [0.5]	Fault length [0.5] D_{cum} [0.5]	D_{cum} [1.0]	Based on D_{cum} and AAR scaling relationship [0.5]; SBK distribution [0.5]
Conditional Probability of Exceedance, *P(D>d)*	Distribution for D/MD^{max} [1.0]	NA	Distribution for *D/AD* [1.0]	Distribution for *D/AD* [0.5] Distribution for D/MD^{max} [0.5] (with MD^{max} = *AD*/0.83)	Distribution for D/D_{cum} [1.0]	For AAR scaling distribution for D/MD^{max}, for SBK scaling distribution for D/D_{cum}

The characterizations of distributed faulting potential using the earthquake approach had the largest uncertainties. The basic evaluation of the frequency of earthquakes was derived from the seismic source characterization for ground motion hazard assessment defined by each team. The probability that an earthquake causes slip at the point of interest was assessed in a variety of ways. The preferred approach utilized a logistic regression model based on analyses of the pattern of historical ruptures (CRWMS M&O 1998a, Section 4.3.2). The widest variations in approaches were those for assessing the distribution for displacement per event on the distributed ruptures.

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6.4 PSHA ASSUMPTIONS

Assumptions made in the PSHA process are briefly summarized below. Assumptions made by the experts in their evaluations are described in detail in Appendices E and F in CRWMS M&O (1998a).

6.4.1 Expert Elicitation

A primary objective of the PSHA was that the evaluations of the experts captured and expressed the range of interpretations and uncertainty of the informed technical community (CRWMS M&O 1998a, Section 2). The selection of the experts and the elicitation as carried out in the PSHA Project follows the guidelines set forth in NUREG/CR-6372 (Budnitz et al. 1997). We assume that this process and the manner in which it was applied allows for this objective to be accomplished.

6.4.2 Model of Randomness

The assumption that the behavior of the earth is generally Poissonian or random is the underlying assumption in all probabilistic hazard analyses. In other words, all earthquakes are considered as independent events with regard to size, time, and location. Although there may be cases where sufficient data and information exists to depart from this assumption, the Poissonian model is generally an effective representation of nature and represents a compromise between the complexity of natural processes, availability of information, and the sensitivity of results of engineering relevance (Budnitz et al. 1997).

6.4.3 Kappa

As discussed in Section 6.3.3.1.1, a median kappa value of 0.0186 sec was assumed appropriate for the reference rock outcrop whose shear wave velocity was 1,900 m/sec. This value was the best estimate for the site area based on the available data. If ongoing investigations indicate that the median value is different than 0.0186 sec, the hazard results may be adjusted accordingly.

6.4.4 Threshold of Damage

The PSHA was computed by integrating recurrence curves for earthquakes of M_W 5.0 and greater. It is established practice that smaller earthquakes produce no damage to well-engineered structures regardless of the ground motions they generate (e.g., McCann and Reed 1990).

6.4.5 Seismic Sources

Two key simplifying assumptions are made in the modeling of seismic sources. First, faults are represented by segmented planar features and rupture is typically considered to occur anywhere along the fault with equal likelihood. Secondly, for areal seismic source zones, it is commonly assumed that the occurrence of earthquakes is uniform in space and time (i.e., there is equal likelihood of occurrence of events at all locations within the zone). Four of the six expert teams did incorporate to some degree, nonuniform spatial occurrence based on the historical earthquake catalog and a nonuniform spatial density function (Table 5).

6.4.6 Ground Motion Attenuation

A simplifying assumption in the development of ground motion attenuation relations that is commonly made and was made by the experts is that the ground motions are a function of only magnitude, distance, faulting style, and location in the hanging wall or footwall (Joyner and Boore 1988; p. 49-58). Other dependencies (such as directivity and stress drop) have been mapped into estimates of the epistemic uncertainties, which are captured in the hazard results.

6.5 PSHA GROUND MOTION HAZARD ASSESSMENT

6.5.1 Methodology

The methodology to calculate the probabilistic ground motion hazard at a site is well established in peer-reviewed literature (Cornell 1968, 1971; McGuire 1978, 1995). This section provides an overview of the approach. For further details about the implementation of the methodology as applied to the Yucca Mountain site, see Section 7.2 of CRWMS M&O (1998a). Calculation of the hazard requires specification of the following three inputs:

- The geometry of a seismic source (e.g., source *i*) relative to the site, and a relationship between rupture size, R(i), and magnitude, M(i), determine the conditional probability distribution of distance *r* from the earthquake rupture to the site (with a given magnitude, M): $f_{R(i)|M(i)}(r|m)$. The types of sources are faults and areal source zones.

- The mean annual rate of occurrence ν_i and magnitude distribution $f_{M(i)}(m)$ of earthquakes occurring on each source *i*. This characterization includes the M_{max} that a seismic source can produce. The M_w scale is used in all the hazard calculations.

- An attenuation relation for the estimation of ground motion amplitude (A) at the site as a function of earthquake magnitude (m) and distance (r), $G_{A|m,r}$ (a*). This characterization includes both an equation for the median amplitude and a standard deviation σ that describes the site-to-site and event-to-event scatter in ground motion amplitude observations for the same magnitude and distance.

These inputs are illustrated on Figure 10, Parts a through c. Figure 10 shows the geometry of a seismic source and the distance distribution for a given value of magnitude. The distribution of magnitude $f_{M(i)}(m)$ for an areal source is typically specified as the doubly truncated exponential distribution. Seismicity for a source with the exponential magnitude distribution is completely specified by the minimum magnitude m_o and parameters a and b. Parameter a is a measure of seismic activity, b is a measure of relative frequency of large versus small events, and log[ν_i $f_{M(i)}(m)$] is proportional to $-bm$ for $m \leq m_{max}$. Except for truncation effects near M_{max}, this is the well-known Gutenberg-Richter relation (Youngs and Coppersmith 1985). The distribution of magnitude $f_{M(I)}(m)$ for a fault is specified by either an exponential distribution, a characteristic distribution (Youngs and Coppersmith 1985; Figure 10b of this document), or a maximum-moment distribution (Wesnousky et al. 1983). The rate information for these three distribution shapes may be specified, respectively, as the rate ν_i, the rate of large earthquakes (magnitude greater than M_{max} - ½), or the SR (for faults only).

The ground motion is modeled by an attenuation function, as illustrated on Figure 10c. The ground motion amplitudes (A) can be for a variety of different parameters, including PGAs, PGVs, and SAs (see Section 6.3.3 for explanation and discussion of parameters evaluated in the PSHA).

Attenuation functions are usually of the form $ln[A] = f(M,R) + \varepsilon$, where A is ground motion amplitude, M is magnitude, R is distance, and ε is a random variable (with mean zero and standard deviation σ) that represents scatter in $ln[A]$ for the same magnitude and distance. The attenuation function is used to calculate $G_{A|m,r}(a^*) = P[A > a^*|m,r]$: the probability that the ground motion amplitude A is larger than a^*, for a given M and R. The seismic hazard over all sources is calculated as a summation:

$$\nu(a^*) = \sum \nu_i \int\int G_{A^*m,r}\left(a^*|m,r\right) f_{M(i)}(m) f_{R(i)|M(i)}\, dm\, dr \qquad \text{(Eq. 6-2)}$$

in which $\nu(a^*)$ is the annual rate of earthquakes that produce amplitudes $A > a^*$ at the site, and the summation is performed over all seismic sources i. The integration on magnitude in Equation 6-2 considers only earthquakes with magnitudes greater than a minimum magnitude m_o, typically taken as M_w 5. Smaller earthquakes are assumed to produce no damage to engineered structures, regardless of the ground motion amplitudes they generate. Thus, both ν and $f_{M(i)}(m)$ are only specified for magnitudes greater than m_o, although smaller magnitudes are considered in the determination of the rate and magnitude distribution.

Equation 6-2 is formulated using the assumption that earthquakes (most particularly, successive earthquakes) are independent in size and location. In all seismic hazard applications, primary interest is focused on computing probabilities for the occurrence of high (rare) ground motions (as a result, the probability of two or more exceedances in 1 year is negligible). Thus, the quantity on the right side of Equation 6-1, which is the annual rate of earthquakes with amplitude $A > a^*$, is a very good approximation to the probability of exceeding amplitude a^* in 1 year.

The calculation of hazard from all sources is performed for multiple values of a^*. The result is a hazard curve, which gives the annual probability of exceedance as a function of a^*. This calculation is performed for multiple measures of ground motion amplitude (i.e., PGA and SA at multiple frequencies).

6.5.2 Treatment of Uncertainty

The most recent PSHA studies distinguish between two types of uncertainty, namely epistemic and aleatory. Aleatory uncertainty (sometimes called randomness) is probabilistic variability that results from natural physical processes. The size, location, and time of the next earthquake on a fault and the details of the ground motion are examples of quantities considered aleatory. In current practice, these quantities cannot be predicted, even with the collection of additional data. Thus, the aleatory component of uncertainty is irreducible. The second category of uncertainty is epistemic (sometimes called simply uncertainty), which results from imperfect knowledge about earthquakes and their effects. An example of epistemic uncertainty is the shape of the magnitude distribution for a given seismic source. In principle, this uncertainty can be reduced with advances in knowledge and the collection of additional data.

These two types of uncertainty are treated differently in advanced PSHA studies. Integration is carried out over aleatory uncertainties to get a single hazard curve (see Equation 6-2), whereas epistemic uncertainties are expressed by incorporating multiple assumptions, hypotheses, models, or parameter values. These multiple interpretations are propagated through the analysis, resulting in a suite of hazard curves and their associated weights. Results are presented as curves showing statistical summaries (e.g., mean, median, fractiles) of the exceedance probability for each ground motion amplitude. The mean and median hazard curves convey the central tendency of the calculated exceedance probabilities. The separation among fractile curves conveys the net effect of epistemic uncertainty about the source characteristics and ground motion prediction on the calculated exceedance probability.

Epistemic uncertainties are associated with each of the three inputs to the seismic hazard evaluation. The seismogenic potential of faults and other geologic features is uncertain, as a result of (1) uncertainty about the tectonic regime operating in the region and (2) incomplete knowledge of these geological features. The geometry of these geologic features is also uncertain. Uncertainty in the rate of seismicity is generally divided into uncertainty in M_{max}, uncertainty in the type of magnitude distribution, uncertainty in the rate parameter (i.e., activity rate, rate of large events, or SR), and uncertainty in b or other shape parameters of the magnitude distribution $f_{M(i)}(m)$. Finally, the attenuation functions are uncertain, which arises from uncertainty about the dynamic characteristics (source, path, and site effects) of earthquake ground motions in the Yucca Mountain vicinity. This uncertainty is large because few strong motions have been recorded in the region. Uncertainties in seismic source characterization and ground motion attenuation relations were quantified by considering inputs from six SSFD expert teams and seven GM experts, and by each team's and expert's own assessment of uncertainty.

That is, each SSFD expert team formulated multiple alternative interpretations about the seismogenic characteristics of potential seismic sources, and assigned weights to these hypotheses according to their credibility given the current state of knowledge and the degree they are supported by data. Each GM expert applied a similar procedure to alternative interpretations about the source, path, and site characteristics affecting ground motions. The development of these seismic source and ground motion interpretations was described previously in Section 6.3.

6.5.3 Ground Motion Hazard Results

All ground motion hazard results were computed for the reference rock outcrop, which corresponds to the proposed waste emplacement depth (represented by Point A on Figure 4). Ground motion was computed at this reference location as a control motion to facilitate the future determination of seismic design input motions for surface locations (Points C and D) and potential waste-emplacement level locations (Point B).

Ground motion hazard was calculated for PGA, PGV, and SA at 0.3, 0.5, 1, 2, 5, 10, and 20 Hz structural frequencies. The computations were based on equal weighting of the six SSFD expert teams' and the seven GM experts' evaluations. Complete data files of the results are located in DTN:MO0004MWDRIFM3.002. The results are presented here in the form of hazard curves showing the mean, median, and 15th and 85th fractile annual exceedance probability for a given ground motion value as shown on Figures 11 through 13. The hazard is also expressed as mean, median, and 15th and 85th fractile SA on uniform hazard spectra (Figures 14 and 15) for target annual exceedance probabilities of 10^{-4} and 10^{-3}, respectively. These hazard results can be used for postclosure to evaluate whether future ground motions contribute to any repository SSC-failure events that occur with a probability greater than 1 in 10,000 years in 10,000 years, as discussed in Section 1. The uniform hazard spectra show SAs with the same annual exceedence probabilities and they can be deaggregated to help develop seismic design inputs. The spectra can be deaggregated on magnitude, distance, and ground motion variability, as shown on Figure 16, to determine controlling earthquakes and provide engineering insights for development of design spectra (McGuire 1995). PGA, PGV, and SA values for the reference rock outcrop are summarized in Table 10 for target design basis hazard annual occurrences of 10^{-3} and 10^{-4}. Note that typographical errors in the PGVs shown in Table 7.1 of CRWMS M&O (1998a) have been corrected in Table 10.

Table 10. Mean SA (g), PGA (g), and PGV (cm/sec) Values
for Reference Rock Outcrop (modified from Table 7.1 of CRWMS M&O 1998a)

Ground Motion Parameter	**Horizontal**		**Vertical**	
	Annual Exceedance Frequency			
SA, *Frequency (Hz)*	**10^{-3}**	**10^{-4}**	**10^{-3}**	**10^{-4}**
0.3	0.051	0.168	0.029	0.105
0.5	0.091	0.278	0.046	0.159
1	0.162	0.471	0.073	0.222
2	0.263	0.782	0.130	0.406
5	0.346	1.083	0.200	0.660
10	0.355	1.160	0.250	0.906
20	0.284	0.951	0.225	0.853
PGA	0.169	0.534	0.112	0.391
PGV	15.4	48.3	7.6	24.9

6.5.4 Sensitivity Analyses

Extensive evaluations of the sensitivity of the hazard results to changes in the input parameters were performed (CRWMS M&O 1998a, Section 7). These sensitivity analyses indicate that the uncertainty in ground motion attenuation was the largest contributor to uncertainty for the ground motion hazard. Each GM expert characterized epistemic uncertainty in the median amplitude and the scatter of ground motion about the median amplitude for a set of magnitude-distance pairs. These evaluations were used to develop a ground motion attenuation relationship for each expert including epistemic uncertainty in the median and the standard deviation of motion about the median estimate. Sensitivity analysis shows that the most important ground motion contributor to uncertainty in the hazard are the within-expert uncertainties about the median ground motion and the standard deviation of motion about the median.

Figure 17 shows the mean hazard for horizontal PGA by individual SSFD teams and for all teams combined. The spread in the curves illustrates the team-to-team epistemic uncertainty, which can be considered a measure of the earth science community's state of knowledge about earthquake processes. This uncertainty is generally less than a factor of 2 and is relatively small, reflecting the large common information base used by the experts, and the success of the expert elicitation process that minimized differences in knowledge and understanding.

With respect to the seismic source characterization, the earthquake recurrence approach (use of either SRs or recurrence intervals) and recurrence models (e.g., characteristic, exponential or maximum moment) were found to contribute the most to uncertainty in the ground motion hazard. M_{max} has a small effect on uncertainty, especially for 10 Hz motions, because a large fraction of the hazard at this frequency comes from more frequent moderate magnitude events at near distances. Geometric fault parameters (e.g., rupture lengths, dips, maximum depths) are minor contributors to uncertainty. These parameters have a moderate effect on the locations of earthquakes and on evaluations of M_{max}, but do not affect earthquake recurrence.

Deaggregation of the mean hazard for an annual exceedance of 10^{-4} shows that at intermediate frequencies (5 to 10 Hz), ground motions are dominated by earthquakes smaller than M_w 6.5 occurring at distances less than 15 km (Figure 16a). The sources of these events are the Paintbrush Canyon - Stagecoach Road and Solitario Canyon faults (or coalesced fault system including these two faults) and the host areal seismic source zone. Dominant events for low frequency ground motions (e.g., 1 to 2 Hz), display a bimodal distribution showing significant contributions to the total hazard from large nearby earthquakes, the same three sources mentioned above, and from M_w 7 and larger earthquakes beyond distances of 50 km (Figure 16b). The latter contribution is mainly from the significantly higher recurrence rates of the Death Valley and Furnace Creek faults. Multiple-rupture interpretations involving comparable seismic moment release on more than one fault (i.e., those requiring modification of the attenuation equations) make a small contribution to the total hazard. Buried strike-slip faults, volcanic seismicity, and seismogenic detachments contribute negligibly to the total hazard.

6.6 PSHA FAULT-DISPLACEMENT HAZARD ASSESSMENT

6.6.1 Methodology

This section describes the methodology used to perform the PSHA calculations for fault displacement at the Yucca Mountain site and the application of this methodology to the demonstration sites within the site area. This presentation uses many of the elements and concepts from the ground motion PSHA that were introduced and described in Section 6.5.1.

Fault displacement PSHA results in the probability that the tectonically induced fault displacement at a given site will exceed any value. The site of interest may or may not be on an active fault. Results are in the form of fault displacement hazard curves, which show annual exceedance probability for values of the displacement.

Of the two approaches for fault displacement PSHA described in Section 6.3.4, the earthquake approach calculates the principal and distributed faulting separately, using different attenuation equations, and then adds them to obtain a total displacement hazard curve. The displacement approach, on the other hand, considers both principal and distributed faulting but does not distinguish between them.

6.6.1.1 Earthquake Approach

The earthquake approach explicitly considers earthquake magnitudes and locations as intermediate variables in the calculation of fault displacement and uses the same seismic source models (i.e., source geometries and magnitude-recurrence models, and their associated uncertainties) that are used in the ground motion PSHA. The only substantive difference between the earthquake approach for fault displacement PSHA and the ground motion analysis described in Section 6.5 relates to the attenuation equations. These differences fall into the following two categories:

1) Because both principal and distributed faulting are nonuniformly distributed, there is a probability of no displacement at the site under consideration, given the occurrence of an earthquake in the vicinity of the site. Thus, the attenuation equation is written as the product of two terms: (1) the probability of nonzero displacement given the occurrence of an earthquake of certain characteristics at a given location and (2) the probability that the displacement at the site will exceed a value d*, given nonzero displacement.

2) Both the probability of nonzero displacement and the conditional probability on the amount of displacement depend on a number of quantities besides just magnitude and distance. These quantities may be grouped into three categories: (1) geometry of the site relative to the rupture (particularly the along-rupture location x/L defined on Figure 8-1 of CRWMS M&O 1998a), (2) characteristics of the principal fault (e.g., total length, cumulative displacement), and (3) characteristics of the feature (fault or fracture, if present) where the site is located (e.g., total length, cumulative displacement).

The resulting attenuation equations for fault displacement are of the form

$$G_D\left(d^*\middle|M,\underline{R},\underline{X}_{principal},\underline{X}_{site}\right)=P[D>0\mid M,\underline{R},\underline{X}_{principal},\underline{X}_{site}]\times P\left[D>d^*\middle|D>0,M,\underline{R},\underline{X}_{principal},\underline{X}_{site}\right] \quad \text{(Eq. 6-3)}$$

where G_D is the attenuation function for fault displacement, $\underline{R}$ represents the location of the rupture relative to the site (not just distance), and $\underline{X}_{principal}$ and $\underline{X}_{site}$ represent characteristics of the principal fault and site (all quantities in $\underline{X}_{principal}$ and $\underline{X}_{site}$ will be represented by $\underline{X}$ for the sake of brevity). Separate attenuation equations are developed for principal and distributed faulting. The attenuation equation for principal faulting is used only in conjunction with the fault where the site is located, if that fault is active. The attenuation equation for distributed faulting is used for all other faults and for the areal source zone containing the site.

The calculation of fault displacement hazard, considering all seismic sources and all earthquake magnitudes, is performed using a modified version of Equation 6-2, namely

$$\nu(d^*)=\sum_i \nu_i \int_{\underline{r}}\int_m G_D\left(d^*\middle|m,\underline{r},\underline{X}\right)f_{M(i)}(m)f_{\underline{R}(i)|M(i)}(\underline{r}m)dm\,d\underline{r} \quad \text{(Eq. 6-4)}$$

where i indicates source number, ν_i is the rate of earthquakes on source i, $f_{M(i)}(m)$ is the probability density function of magnitude, and $\mathrm{f}_{\underline{\mathrm{R}}(\mathrm{i})|\mathrm{M}(\mathrm{i})|}(\underline{\mathrm{r}}\mathrm{m})$ is the probability density function of earthquake location (given magnitude). The calculation of fault displacement hazard given by the equation above is performed for multiple values of d^*. The result is a hazard curve, which gives the annual probability of exceedance as a function of d^*.

As in the case of ground motions, the primary interest is focused on computing probabilities for large but rare displacements. As a result, the probability of two or more events with D > d* in one year is negligible. Thus, the quantity on the right side of Equation 6-4, which is the annual rate of earthquakes with displacement $D > d^*$ is a good approximation to the probability of exceeding displacement d^* in one year. If the quantity of interest is the maximum single-event fault displacement during a long time period T, one can use the equation

$$P\,[\,D_{\max}\,(T) > \mathrm{d}^*] = 1 - exp[-\nu(d^*)T] \quad \text{(Eq. 6-5)}$$

It should be emphasized that these hazard results are applicable to single events. If the quantity of interest is the cumulative displacement from more than one earthquake over a long time period, which is not the intent in this study, it is necessary to use the theory of compound Poisson processes.

6.6.1.2 Implementation of the Earthquake Approach

Calculations for the earthquake approach consider all local faults, as well as the host areal source zone(s). The regional faults do not contribute to distributed fault displacement because the distributed displacement attenuation equations decay rapidly with distance, given the models formulated by the SSFD expert teams.

The rate portion of the attenuation equations for principal displacement (i.e., the first term in Equation 6-3) consists of a portion that depends on *x/L* (i.e., unity for *x/L* in the interval [0,1], zero otherwise), and a magnitude-dependent portion. The magnitude-dependent portion is considered a logistic function of magnitude, except by one team that considers the probability distribution of hypocentral depth, the magnitude-dependent rupture width, and the down-dip geometry of the fault. The rate portion of the attenuation equations for fault displacement is a logistic function of magnitude and distance, or PGV at the site. The rate portion for distributed faulting also includes the probability P[C] that the site is capable of fault displacement. This probability represents epistemic uncertainty (unless it is exactly zero or unity).

The distribution portion of the attenuation equations for principal and distributed displacement (i.e., the second term in Equation 6-3) is specified as an expression for the scale parameter of the distribution (e.g., mean displacement given magnitude, *x/L*, etc.), and information about the shape and spread of the distribution. For several teams, this expression consists of a product of several random terms. For instance, several teams calculate the principal displacement as the product of the MD (taken as lognormal, with a median value that depends on magnitude) times a random shape function (which, for a given x/L, takes the form of a beta distribution with parameters that depend on x/L). In all these instances, these products are approximated using lognormal probability distributions, with medians and coefficients of variation computed using the well-known approximations for products of random variables. The accuracy of all these approximations was tested by comparing the exact and approximate distribution shapes.

There are also situations where the distribution portion of the attenuation equation for distributed displacement is not a function of the earthquake magnitude or distance, and depends only on some characteristic of the site. This approach constitutes a hybrid between the earthquake and displacement method, where the occurrence portion of the model considers earthquakes, but the distance-distribution portion depends only on the characteristics of the site.

6.6.1.3 Displacement Approach

The displacement approach uses a direct characterization of the occurrence rate of displacement events at the site and the probability distribution of displacement per event, without using earthquake magnitude and location as intermediate variables. The occurrence rate information may be provided as direct values of the occurrence rate λ or in the form of a SR divided by an average displacement per event. Specification of the probability distribution of displacement per event P[D>d* | event] is in the form of a scale parameter (such as the average displacement per event $\overline{D}_E$, maximum displacement D_{max}, or cumulative displacement D_{cum}) and information about the shape and spread of the distribution.

Calculation of the fault displacement hazard curve for the displacement approach (under the assumption of rare events discussed above) is straightforward, namely:

$$\nu(d^*) = \lambda \, P\left[D > d^* \middle| event\right] \qquad \text{(Eq. 6-6)}$$

6.6.1.4 Implementation of the Displacement Approach

Although calculation of the hazard curve for this approach does not require integration over magnitudes and distances or summation over seismic sources, a logic tree analysis is required because the expert teams specified multiple alternatives for the various elements of the model and for the characteristics of the site.

6.6.2 Treatment of Uncertainty

As with the ground motion PSHA methodology (discussed in Section 6.5.1), the formulations given above for the earthquake and displacement approaches for the fault displacement PSHA represent the aleatory uncertainty in the natural phenomena of tectonically-induced fault displacement. Mathematically, aleatory uncertainty is represented by the rates and probability distributions in Equations 6-3, 6-4, and 6-5. Epistemic uncertainty is associated with imperfect knowledge about these phenomena. In the earthquake approach, epistemic uncertainty is in the seismic source characterization, the attenuation equations, and the characteristics of the site that affect fault displacement. In the displacement approach, epistemic uncertainty is in the two elements of the model, namely the rate information and the parameters of the displacement per event distribution, as well as in the characteristics of the site that affect fault displacement.

Epistemic uncertainties in seismic source characterization and fault displacement attenuation equations are quantified by considering inputs from the six SSFD expert teams, and by each team's own assessment of epistemic uncertainty. Each expert team selects an approach for the fault displacement PSHA (earthquake, displacement, or a weighted combination of both), then formulates multiple alternative interpretations for the fault displacement attenuation equations (if using the earthquake approach) or for the rate and the distribution of displacement per event (if using the displacement approach). Calculations for the earthquake approach consider each expert team’s fault displacement attenuation equations in conjunction with that team's source characterization.

6.6.3 Fault Displacement Hazard Results

Probabilistic fault displacement hazard was calculated at the nine sites within the site area proposed for the repository (Figure 3). Two of the sites (7 and 8) have four displacement histories specified to represent actual fault and fracture conditions that have been mapped at Yucca Mountain.

All of the teams considered Sites 1 and 2 to be on principal faults. Two teams also considered some potential for principal faulting hazard at Site 4 because they interpreted some probability that the Ghost Dance fault is seismogenic. One team also made the interpretation that Site 6 in Dune Wash lies on the West Dune Wash fault and has some probability of being subject to principal faulting hazard.

The teams varied widely in their assessments of the probability that distributed faulting could occur in future earthquakes at Sites 3 through 9, which are away from the block-bounding faults and principal faults. These assessments were based on fault orientation, cumulative slip, and structural relationships. One team's interpretation was that all features with some evidence of cumulative displacement are capable of displacement in future earthquakes. Another team's interpretation was that for most of these features, the probability that they are capable of displacement in future earthquakes is low. All the teams considered that the probability of displacement at a point in intact rock resulting from a future earthquake is either extremely low or zero.

The integrated hazard results provide a representation of fault displacement hazard and its uncertainty at the nine sites, based on the interpretations and parameters developed by the SSFD expert teams. Complete data files of the results are located in DTN: MO0004MWDRIFM3.002. Separate results are shown here for each site in the form of summary fault displacement hazard curves (Figures 18 through 22). Note that separate curves are not shown for Site 7d and 8d because all results are below an annual exceedance probability of 10^{-8} (p. 8-6 of CRWMS M&O 1998a). Also note that for some of the sites, the median and/or 15th percentile curves are not shown because the values are below the range of the plots (for example, Site 7, Figure 21). Additionally, for many of the sites, mean values can actually exceed the 85th percentiles at lower probabilities (Figures 18 through 22). This is due to the skewed distributions resulting from large uncertainties as discussed further below. Table 11 contains a summary of the mean displacement hazard results for the two target preclosure design annual exceedance probabilities, 10^{-4} and 10^{-5}, at the nine sites.

With the exception of the block-bounding Bow Ridge and Solitario Canyon faults (Sites 1 and 2, respectively), the mean displacements are all 0.1 cm or less at a 10^{-5} annual exceedance probability (Table 11). For the Bow Ridge and Solitario Canyon faults at 10^{-5} annual exceedance probability, the mean displacements are 7.8 and 32 cm, respectively (Figure 18; Table 11). Thus, sites not located on a block-bounding fault (i.e., sites on the intrablock faults, other small faults, shear fractures, and intact rock) are assessed to have displacements of 0.1 cm or less for target preclosure design hazard annual exceedance probabilities (Figures 19 through 22; Table 11).

Due to the large uncertainties, extrapolating the displacement hazard curves to lower exceedance probabilities for performance assessment may require additional considerations in applying the results. The hazard results for the Bow Ridge fault (Figure 18a) suggest 2 and greater than 5 m displacements corresponding to 10^{-8} median and mean annual exceedance probabilities, respectively. The large difference between the mean and median hazard results is a consequence of the very large knowledge uncertainty about modeling fault displacement hazard. This large uncertainty is further highlighted by the fact that the mean hazard curve is above the 85th percentile for annual exceedance probabilities below 10^{-7}, illustrating that the hazard results are driven by large modeling uncertainty at these low annual exceedance probabilities. The projected hazard curves at 10^{-8} annual exceedance probabilities for the Solitario Canyon fault suggest median and mean displacements of about 3.5m, and more than 5 m, respectively. Similar to the Bow Ridge fault, the mean displacement hazard curve is larger than the median curve for low probabilities. Due to such large uncertainties controlling the mean hazard curve at low probabilities (below 10^{-6}) it may be appropriate for some applications to use the median hazard curve, or some intermediate value between the mean and median, to determine fault displacement hazard values at these low annual exceedance probabilities.

Geologic data for these faults also support using median rather than mean displacement values at low exceedance probabilities. Paleoseismic data indicate displacements per event were 80 cm or less for the Bow Ridge fault (maximum estimate for the last two to three surface-faulting events that occurred within the past 340,000 years), and 140 cm or less for the Solitario Canyon fault (maximum estimate for the last four to six events that occurred within the past 200,000 years) (CRWMS M&O 1998b, Section 12.3). Even cumulative displacements for these same time periods are less than the mean hazard values at 10^{-8} exceedance probabilities. The short lengths of these faults also suggest that mean displacement values exceed what is physically credible for correspondingly small rupture areas. For example, the total end to end length of the local faults is less than 33 km. Given a maximum surface rupture length of 33 km, empirical relations yield expected maximum displacements of 1.3 and 1.5 m for all type and normal slip faults, respectively (Wells and Coppersmith 1994). Even at two standard deviations, maximum displacements based on surface rupture are less than 3 m.

Table 11. Mean Displacement Hazard at Nine Demonstration Sites
(Table 8-1 from CRWMS M&O 1998a)

Site[1]	Location	Mean Displacement (cm) 10^{-4} Annual Exceedance Probability	Mean Displacement (cm) 10^{-5} Annual Exceedance Probability
1	Bow Ridge fault	<0.1	7.8
2	Solitario Canyon fault	<0.1	32
3	Drill Hole Wash fault	<0.1	<0.1
4	Ghost Dance fault	<0.1	<0.1
5	Sundance fault	<0.1	<0.1
6	Unnamed fault west of Dune Wash	<0.1	<0.1
7	100 m east of Solitario Canyon fault		
7a	2-m small fault	<0.1	<0.1
7b	10-cm shear	<0.1	<0.1
7c	Fracture	<0.1	<0.1
7d	Intact rock	<0.1	<0.1
8	Between Solitario Canyon and Ghost Dance		
8a	2-m small fault	<0.1	<0.1
8b	10-cm shear	<0.1	<0.1
8c	Fracture	<0.1	<0.1
8d	Intact rock	<0.1	<0.1
9	Midway Valley	<0.1	0.1

[1] Location shown on Figure 3.

6.6.4 Sensitivity Analyses

Extensive evaluations of the sensitivity of hazard results to evaluated parameters were performed (CRWMS M&O 1998a, Section 8). Figure 23 illustrates the team-to-team variation in the mean fault displacement hazard for Site 1. The team-to-team uncertainty is significantly larger than is found for ground motion hazard. We believe this relatively larger scientific uncertainty appropriately reflects the early stage of development of the methodology for probabilistic assessments of fault displacement hazard.

A positive correlation between the amount of geologic data available at a site and the uncertainty in the calculated fault displacement hazard at that site is observed, as should be expected. For sites with significant geologic data, the team-to-team uncertainty is less than 1 order of magnitude. For sites with few or no data, the team-to-team uncertainty may span 3 orders of magnitude. The larger uncertainty at these sites is considered to be due to data uncertainty (i.e., less certain constraints on fault displacement characterization models).

While the fault displacement hazard results display large uncertainty, the hazard levels are quite low. Sites with the highest fault displacement hazard show uncertainties comparable to those obtained in the ground motion PSHA. Sites with low hazard show much higher uncertainties. While the fault displacement hazard results overall have significantly greater uncertainty than the ground motion hazard results, they are considered robust by virtue of the extensive efforts at expert elicitation and feedback, as well as the methodological developments that were undertaken as part of this study.

7. CONCLUSIONS

The main conclusions for this AMR are the same as those for the PSHA report (CRWMS M&O 1998a). The earthquake hazards from ground shaking and fault displacement have been evaluated for the potential geologic repository at Yucca Mountain (DTN: MO0004MWDRIFM3.002). PSHA using multiple expert interpretations to capture scientific uncertainty have been employed. The resulting level of ground motion hazard, calculated for a defined rock condition (Point A on Figure 4), is comparable to moderate tectonically and seismically active sites elsewhere in the Basin and Range province such as the Rio Grande rift in New Mexico and southern Colorado (Wong and Olig 1998). For example, horizontal PGAs at Yucca Mountain with annual exceedance frequencies of 10^{-3} and 10^{-4} are 0.169 and 0.534 g, respectively (Table 10). The hazard at Yucca Mountain is lower than elsewhere in the Basin and Range tectonic province, for example, locations along the Wasatch fault in central Utah.

The approaches used in the probabilistic fault displacement hazard analysis were developed specifically for the Yucca Mountain site and represent the state of the art in this type of hazard evaluation. The results indicate that fault displacement hazard is not a seismic design issue for the repository, although block-bounding faults should be avoided in the layout of the underground facilitates in accordance with YMP (1997a).

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8. INPUTS AND REFERENCES

8.1 DOCUMENTS CITED

Abrahamson, N.A.; and Silva, W.J. 1997. "Empirical Response Spectral Attenuation Relations for Shallow Crustal Earthquakes." *Seismological Research Letters*, 68, (1), 94-127. El Cerrito, CA: Seismological Society of America. TIC: 240553

Anderson, R.E.; Bucknam, R.C.; Crone, A.J.; Haller, K.M.; Machette, M.N.; Personius, S.F.; Barnhard, T.P.; Cecil, M.J.; and Dart, R.L. 1995. *Characterization of Quaternary and Suspected Quaternary Faults, Regional Studies, Nevada and California*. Open-File Report 95-599. Denver, CO: U.S. Geological Survey. ACC: MOL.19960924.0562.

Anderson, R.E.; Crone, A.J.; Machette, M.N.; Bradley, L.A.; and Diehl, S.F. 1995. *Characterization of Quaternary and Suspected Quaternary Faults, Amargosa Area, Nevada and California.* Open File Report 95-613. Denver CO: U.S. Geological Survey. TIC: 246589.

Beason, S.C.; Turlington, G. A.; Lung, R.C.; Eatman, G.L.W.; Ryter, D., and Barr, D.L 1996. *Geology of the North Ramp-Station 0+60 to 4+00, Exploratory Studies Facility, Yucca Mountain Project, Yucca Mountain, Nevada*. Denver, Colorado: U.S. Geological Survey. ACC: MOL.19970106.0449.

Becker, A.M.; and Abrahamson, N.A. 1997. "Stress Drops in Normal Faulting Earthquakes." *Seismological Research Letters,* 68, (2), 322. El Cerrito, California: Seismological Society of America. TIC: 247049.

Bell, M.J. 1996. "Issue Resolution Status Report on 'Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazard at Yucca Mountain'." Letter to Dr. S. Brocoum DOE/YMSCO, July 26, 1996, with enclosure. Washington D.C.: U.S. Nuclear Regulatory Commission. ACC: MOV.19980417.0079.

Boore, D.M.; Joyner, W.B.; and Fumal, T.E. 1997. "Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes – A Summary of Recent Work. *Seismological Research Letters,* 68, (1), 128-153. El Cerrito, CA: Seismological Society of America. TIC: 240882.

Campbell, K.W. 1997. "Empirical Near-Source Attenuation Relationships for Horizontal and Vertical Components of Peak Ground Acceleration, Peak Ground Velocity, and Pseudo-Absolute Acceleration Response Spectra." *Seismological Research Letters,* 68, (1), 154-179. El Cerrito, CA: Seismological Society of America. TIC: 241762.

Cornell, C.A. 1968. "Engineering Seismic Risk Analysis." *Bulletin of the Seismological Society of America*, 58, (5), 1583-1606. El Cerrito, CA: Seismological Society of America. TIC: 237493.

Cornell, C.A. 1971. "Probabilistic Analysis of Damage to Structures Under Seismic Loads." Chapter 27 of *Dynamic Waves in Civil Engineering,* Howells, D.A., Haigh, I.P., and Taylor, C., eds. New York: Wiley Interscience. TIC: 241003.

CRWMS M&O (Civilian Radioactive Waste Management System, Management and Operating Contractor). 1998a. *Probabilistic Seismic Hazard Analyses for Fault Displacement and Vibratory Ground Motion at Yucca Mountain, Nevada*. Milestone SP321M3. Wong, I.G. and Stepp, J.C., coordinators. Oakland, California: CRWMS M&O. ACC: MOL.19981207.0393.

CRWMS M&O. 1998b. *Yucca Mountain Site Description*, B00000000-01717-5700-00019, Revision 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19981202.0492.

CRWMS M&O. 1999a. *Characterize Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada.* TDP-CRW-GS-000001, Revision 2. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19991110.0438.

CRWMS M&O. 1999b. *Analysis to Characterize the Framework for Seismicity and Structural Deformation at Yucca Mountain, Nevada*. Activity Evaluation, July 26, 1999. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.19990917.0050.

CRWMS M&O. 2000a. *Disruptive Events Process Model Report*. TDR-NBS-MD-000002 REV 00. Las Vegas, Nevada: CRWMS M&O. URN-0230.

CRWMS M&O. 2000b. *Fault Displacement Effects on Transport in the Unsaturated Zone*. ANL-NBS-HS-000020. Las Vegas, Nevada: CRWMS M&O. URN-0035.

CRWMS M&O. 2000c. *Effects of Fault Displacement on Emplacement Drifts*. ANL-EBS-GE-000004 REV 00. Las Vegas, Nevada: CRWMS M&O. ACC: MOL.20000228.0529.

CRWMS M&O. 2000d. *Disruptive Events FEPS*. ANL-WIS-MD-000005 REV 00. Las Vegas, Nevada: CRWMS M&O. URN-0017.

CRWMS M&O. 2000e. *Development of Preliminary Seismic Design Ground Motion Inputs for a Geologic Repository at Yucca Mountain, Nevada*. ANL-CRW-GS-00001 REV 01. Las Vegas, Nevada: CRWMS M&O. URN-0229

Day, W.C.; Dickerson, R.P.; Potter, C.J.; Sweetkind, D.S.; San Juan, C.A.; Drake II, R.M.; and Fridrich, C.J. 1998. *Bedrock Geologic Map of the Yucca Mountain Area, Nye County, Nevada*. Geologic Investigations Series I-2627. Denver, Colorado: U.S. Geological Survey. ACC: MOL. 19981014.0301.

DOE (U.S. Department of Energy). 1997. *Audit Report of United States Geological Survey at Denver, Colorado.* USGS-ARP-98-01, Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19980204.0037.

DOE. 1998. *Quality Assurance Requirements and Description.* DOE/RW-0333P, Revision 8. Washington D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL 19980601.0022.

DOE 2000. *Quality Assurance Requirements and Description*. DOE/RW-00333P, Revision 9. Washington D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19991028.0012.

Dyer, J.R. 1999. "Revised Interim Guidance Pending Issuance of New U.S. Nuclear Regulatory Commission (NRC) Regulations (Revision 01, July 22, 1999), for Yucca Mountain, Nevada." Letter from Dr. J.R. Dyer (DOE/YMSCO) to Dr. D.R. Wilkins (CRWMS M&O), September 3, 1999, OL&RC:SB-1714, with enclosure, "Interim Guidance Pending Issuance of New NRC Regulations for Yucca Mountain (Revision 01)". ACC: MOL.19990910.0079.

EPRI (Electric Power Research Institute). 1986. *Seismic Hazard Methodology for the Central and Eastern United States, Volume 1: Methodology.* EPRI NP-4726. Palo Alto, CA: Electric Power Research Institute. TIC: 222575.

Frankel, A. 1995. "Mapping Seismic Hazard in the Central and Eastern United States. *Seismological Research Letters,* 66, (4), 8-21. El Cerrito, CA: Sesmological Society of America. TIC: 243318.

Fridrich, C.J.; Whitney, J.W.; Hudson, M.R.; and Crowe, B.M. 1999. "Space-Time Patterns of Lake Cenozoic Extension, Vertical-Axis Rotation, and Volcanism in the Crater Flat Basin, Southwest Nevada." *Cenozoic Basins of the Death Valley Region,* Wright, L.A. and Troxel, B.W., eds. Special Paper 333, p. 197-212. Boulder, Colorado: Geological Society of America. TIC: 245358.

Joyner, W.B. and Boore, D.M. 1988. "Measurement, Characterization, and Prediction of Strong Ground Motion." *Proceedings, Conference on Earthquake Engineering and Soil Dynamics II: Recent Advances in Ground-Motion Evaluation, Geotechnical Division/American Society of Civil Engineers, Park City, Utah, June 27-30,* J.L. Von Thun, ed., p. 43-102. New York, New York: American Society of Civil Engineers. TIC: 241219.

Keefer, W.R. and Pezzopane, S.K. 1996. "Quaternary Faults in the Yucca Mountain Region." Chapter 3 of *Seismotectonic Framework and Characterization of Faulting at Yucca Mountain, Nevada,* Whitney, J.W., ed. Milestone 3GSH100M. Denver, CO: U.S. Geological Survey. TIC: 237980.

Kennedy, R.P. and Ravindra, M.K. 1984. "Seismic Fragilities for Nuclear Power Plant Risk Studies." *Nuclear Engineering and Design,* 79, 47-68. Amsterdam, The Netherlands: Elsevier Science Publishers B.V. (North-Holland Physics Publishing Division). TIC: 243985.

McCann, M.W., Jr., and Reed, J.W. 1990. "Lower Bound Earthquake Magnitude for Probabilistic Seismic Hazard Evaluation.*" Nuclear Engineering and Design*, 123, 143-153. Amsterdam, The Netherlands: Elsevier Science Publishers. TIC: 247150.

McGarr, A. 1984. “Scaling of Ground Motion Parameters, State of Stress, and Focal Depth.” *Journal of Geophysical Research*, 89, (B8), 6969-6979. Washington, D.C.: American Geophysical Union. TIC: 222577.

McGuire, R.K. 1978. *FRISK*: *Computer Program for Seismic Risk Analysis Using Faults as Earthquake Sources.* Open-File Report 78-1007. Denver, CO: U.S. Geological Survey. ACC: NNA.19891107.0112.

McGuire, R.K. 1995. “Probabilistic Seismic Hazard Analysis and Design Earthquakes – Closing the Loop.” *Bulletin of the Seismological Society of America,* 85, (5), 1275-1284. El Cerrito, CA: Seismological Society of America. TIC: 232947.

McKague, H.L.; Stamatakos, J.A.; and Ferrill, D.A. 1996. *Type I Faults in the Yucca Mountain Region*. CNWRA 96-007, Revision 1. San Antonio, TX: Center for Nuclear Waste Regulatory Analyses. TIC: 232061.

NRC (U.S. Nuclear Regulatory Commission). 1999. *Issue Resolution Status Report Key Technical Issue: Structural Deformation and Seismicity.* Revision 2. Washington, D.C.: U.S. Nuclear Regulatory Commission. ACC: MOL.19991214.0623.

Pezzopane, S.K., 1996. “Relevant Earthquake Sources.” Chapter 11 of *Seismotectonic Framework and Characterization of Faulting at Yucca Mountain, Nevada,* Whitney, J.W., ed. Milestone 3GSH100M. Denver, CO: U.S. Geological Survey. TIC: 237980.

Pezzopane, S.K.; Menges, C.M.; and Whitney, J.W. 1994. “Quaternary Paleoseismology and Neogene Tectonics at Yucca Mountain, Nevada.” *Proceedings of the Workshop on Paeloseismology, September 18-22, Marshall, California,* Prentice, C.S. Schwartz, D.P., and Yeats, R.S., eds., 149-152. Open-File Report 94-568. Denver, CO: U.S. Geological Survey. ACC: MOL.19960305.0290.

Piety, L.A. 1996. *Compilation of Known or Suspected Quaternary Faults Within 100 km of Yucca Mountain, Nevada and California*. Open File Report 94-112. Denver, CO: U.S. Geological Survey. ACC: MOL.19971009.0003.

Sabetta, F. and Pugliese, A. 1996. “Estimation of Response Spectra and Simulation of Nonstationary Earthquake Ground Motions.” *Bulletin of the Seismological Society of America,* 86, (2), 337-352. El Cerrito, CA: Seismological Society of America. TIC: 241042.

Sadigh, K.; Chang, C.-Y.; Egan, J.A.; Makdisi, F.; and Youngs, R.R. 1997. “Attenuation Relationships for Shallow Crustal Earthquakes Based on California Strong Motion Data.” *Seismological Research Letters,* 68, (1), 180-189. El Cerrito, CA: Seismological Society of America. TIC: 243233.

Savage, J.C.; Svarc, J.L.; and Prescott, W.H. 1999. “Strain Accumulation at Yucca Mountain, Nevada, 1983-1998.” *Journal of Geophysical Research,* 104, (B8), 17627-17631. Washington, D.C.: American Geophysical Union. TIC: 245645.

Schneider, J.F.; Abrahamson, N.A.; and Hanks, T.C. 1996. *Ground Motion Modeling of Scenario Earthquakes at Yucca Mountain, Final Report for Activity 8.3.1.17.3.3.* Volume 1. Denver, CO: U.S. Geological Survey. ACC: MOL.19980617.0477.

Spudich, P.; Fletcher, J.B.; Hellweg, M.; Boatwright, J.; Sullivan, C.; Joyner, W.B.; Hanks, T.C.; Boore, D.M.; McGarr, A.; Baker, L.M.; and Lindh, A.G. 1996. *Earthquake Ground Motions in Extensional Tectonic Regimes.* Open-File Report 96-292. Menlo Park, CA: U.S. Geological Survey. TIC: 245279.

Stokoe, K.H.; Darendeli, M.B.; and Moulin, B.S. 1998. *Laboratory Evaluation of the Dynamic Properties of Intact Tuff Specimens from the Yucca Mountain Site.* Geotechnical Engineering Report GR98-1. Austin, TX: University of Texas at Austin. ACC: MOL.19990827.0153.

Su, F.; Anderson, J.G.; Brune, J.N.; and Yuehua, Z. 1996. "A Comparison of Direct S-Wave and Coda-Wave Site Amplification Determined from Aftershocks of the Little Skull Mountain Earthquake." *Bulletin of the Seismological Society of America,* 86, (4), 1006-1018. El Cerrito, CA: Seismological Society of America. TIC: 236585.

Toro, G. 1998. *Probabilistic Seismic Hazard Analysis (PSHA) Software Documentation for Limited Requirements Software Programs MEAN and CMB-FRAC, Supporting Documentation*. ACC: MOL.19991104.0337.

Wells, D.L.; and Coppersmith, K.J. 1994. "New Empirical Relationships Among Magnitude, Rupture Length, Rupture Width, Rupture Area, and Surface Displacement." *Bulletin of the Seismological Society of America*, 84, (4), 974-1002. El Cerrito, CA: Seismological Society of America. TIC: 226273.

Wemheuer, R.F. 1999. "First Issue of FY00 NEPO QAP-2-0 Activity Evaluations." Interoffice correspondence from R.F. Wemheuer (CRWMS M&O) to R.A. Morgan (CRWMS M&O), October 1, 1999, LV.NEPO.RTPS.TAG.10/99-155, with enclosures, Activity Evaluations. ACC: MOL.19991028.0162.

Wesnousky, S.G.; Scholz, C.H.; Shimazaki, K.; and Matsuda, T. 1983. "Earthquake Frequency Distribution and the Mechanics of Faulting." *Journal of Geophysical Research,* 88, (B11), 9331-9340. Washington, D.C.: American Geophysical Union. TIC: 241700.

Westaway, R.; and Smith, R.B. 1989. "Strong Ground Motion in Normal-Faulting Earthquakes." *Geophysical Journal*, 96, 529-599. New York: Gordan and Breach Science Publishers. TIC: 237524.

Whitney, J.W., ed. 1996. *Seismotectonic Framework and Characterization of Faulting at Yucca Mountain, Nevada*. Milestone 3GSH100M. Denver, CO: U.S. Geological Survey. ACC: MOL.19970129.0041; MOL.19970129.0042; MOL.19970129.0043; MOL.19970129.0044; MOL.19970129.0045; MOL.19970129.0046; MOL.19970129.0047; MOL.19970129.0048; MOL.19970129.0049; MOL.19970129.0050; MOL.19970129.0051; MOL.19970129.0052; MOL.19970129.0053; MOL.19970129.0054; MOL.19970129.0055; MOL.19970129.0056;

MOL.19970129.0057; MOL.19970129.0058; MOL.19970129.0059; MOL.19970129.0060; MOL.19970129.0061; MOL.19970129.0062.

Wong, I.G. and Olig, S.S. 1998. "Seismic Hazards in the Basin and Range Province: Perspectives from Probabilistic Analyses." In *Western States Seismic Policy Council Proceedings Volume, Basin and Range Province Seismic-Hazards Summit*, Lund, W.R., ed., 110-127. Miscellaneous Publication 98-2. West Valley, Utah: Utah Geological Survey. TIC: 246993.

Youngs, R.R. and Coppersmith, K.J. 1985. "Implications of Fault Slip Rates and Earthquake Recurrence Models to Probabilistic Seismic Hazard Estimates. *Bulletin of the Seismological Society of America,* 75, (4), 939-964. El Cerrito, CA: Seismological Society of America. TIC: 237426.

Youngs, R.R.; Swan, F.H.; Power, M.S.; Schwartz, D.P.; and Green, R.K. 1987. "Probabilistic Analysis of Earthquake Ground Shaking Hazard Along the Wasatch Front, Utah." Chapter M of *Assessment of Regional Earthquake Hazards and Risk Along the Wasatch Front, Utah,* Gori, P.L. and Hays, W.W., eds. Open-File Report 87-585, v.2, p. M1-M110. Reston, VA: U.S. Geological Survey. TIC: 245616.

YMP (Yucca Mountain Project). 1997a. *Preclosure Seismic Design Methodology for a Geologic Repository at Yucca Mountain*. Topical Report YMP/TR-003-NP, Revision 2. Las Vegas, NV: DOE/Yucca Mountain Site Characterization Office. ACC: MOL.19971009.0412.

YMP. 1997b. *Methodology to Assess Fault Displacement and Vibratory Ground Motion Hazards at Yucca Mountain*. Topical Report YMP/TR-002-NP, Revision 1. Las Vegas, NV: DOE/Yucca Mountain Site Characterization Office. ACC: MOL.19971016.0777.

8.2 CODES, STANDARDS, REGULATIONS, AND PROCEDURES

AP-3.10Q, Rev. 2, ICN 0, *Analyses and Models*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20000217.0246.

AP-AC-1Q, Rev. 0, ICN 0, *Expect Elicitation*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19991019.0014.

AP-SI.1Q, Rev. 1, ICN 0, *Software Management*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.19990630.0395.

AP-SI.1Q, Rev. 2, ICN 4, *Software Management*. Washington, D.C.: U.S. Department of Energy, Office of Civilian Radioactive Waste Management. ACC: MOL.20000223.0508.

Budnitz, R.J.; Apostolakis, G; Boore, D.M.; Cluff, L.S.; Coppersmith, K.J.; Cornell, C.A.; and Morris, P.A. 1997. *Recommendations for Probabilistic Seismic Hazard Analysis – Guidance on Uncertainty and Use of Experts.* NUREG/CR-6372. Two volumes. Washington, D.C. U.S. Nuclear Regulatory Commission. TIC: 235076; 235074.

Kotra, J.P.; Lee, M.P; Eisenberg, N.A.; and DeWispelare, A.R. 1996. *Branch Technical Position on the Use of Expert Elicitation in the High-Level Radioactive Waste Program*. NUREG-1563. Washington, DC: U.S. Nuclear Regulatory Commission. TIC: 226832.

Nuclear Waste Policy Act of 1982. 42 U.S.C. 10101 et seq.

QAP-2-0, Rev 5, ICN 1, *Conduct of Activities*. Las Vegas, NV: CRWMS M&O. ACC: MOL.19991109.0221.

QAP-2-3, Rev. 10. *Classification of Permanent Items*. Las Vegas, NV: CRWMS M&O. ACC: MOL.19990316.0006.

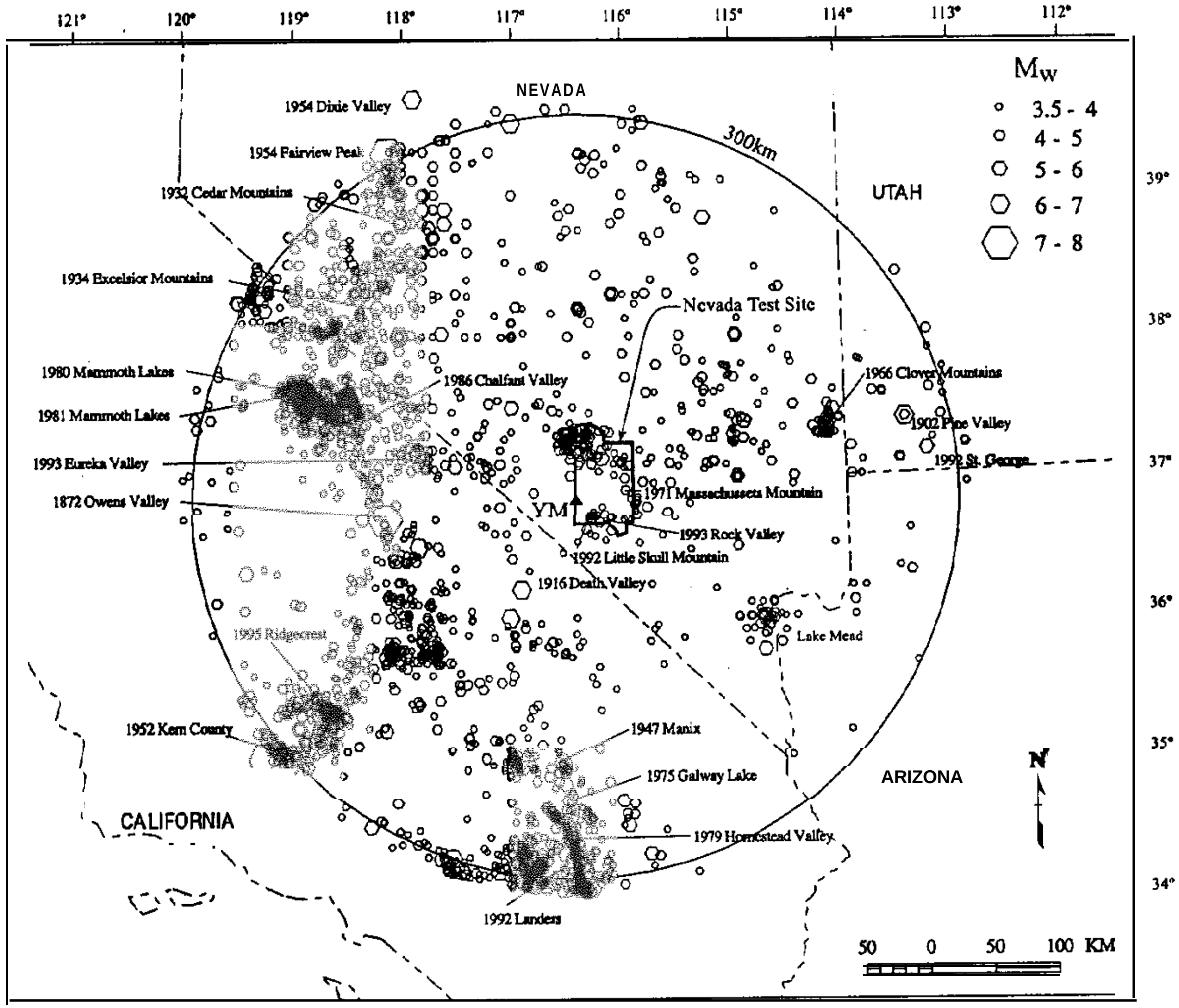
USGS (U.S. Geological Survey). 1996. "Section 16 - Scientific Expert Elicitation." *Chapter 3-Scientific Investigation and Design Control, Management Procedures Manual*. YMP-USGS-QMP-3.16, Rev. 0. Denver, Colorado: U.S. Geological Survey. ACC: MOL.19970127.0096.

USGS. 1997. "Section 3 – Software." *Chapter 3 – Scientific Investigation and Design Control, Management Procedures Manual.* YMP-USGS-QMP-3.03, Rev. 7. Denver, Colorado: U.S. Geological Survey. ACC: MOL.19971218.0474.

USGS. 1998. *QMP-3.16R0*, *Scientific Expert Elicitation*. YMPB Modification to YMPB Quality Management Procedure. QMP 3.16, RO-M1. Denver, Colorado: U.S. Geological Survey. ACC: MOL.19980720.0024.

8.3 SOURCE DATA, LISTED BY DATA TRACKING NUMBER

MO0004MWDRIFM3.002. Results of the Yucca Mountain Probabilistic Seismic Hazard Analysis (PSHA). Submittal date: 4/14/2000.

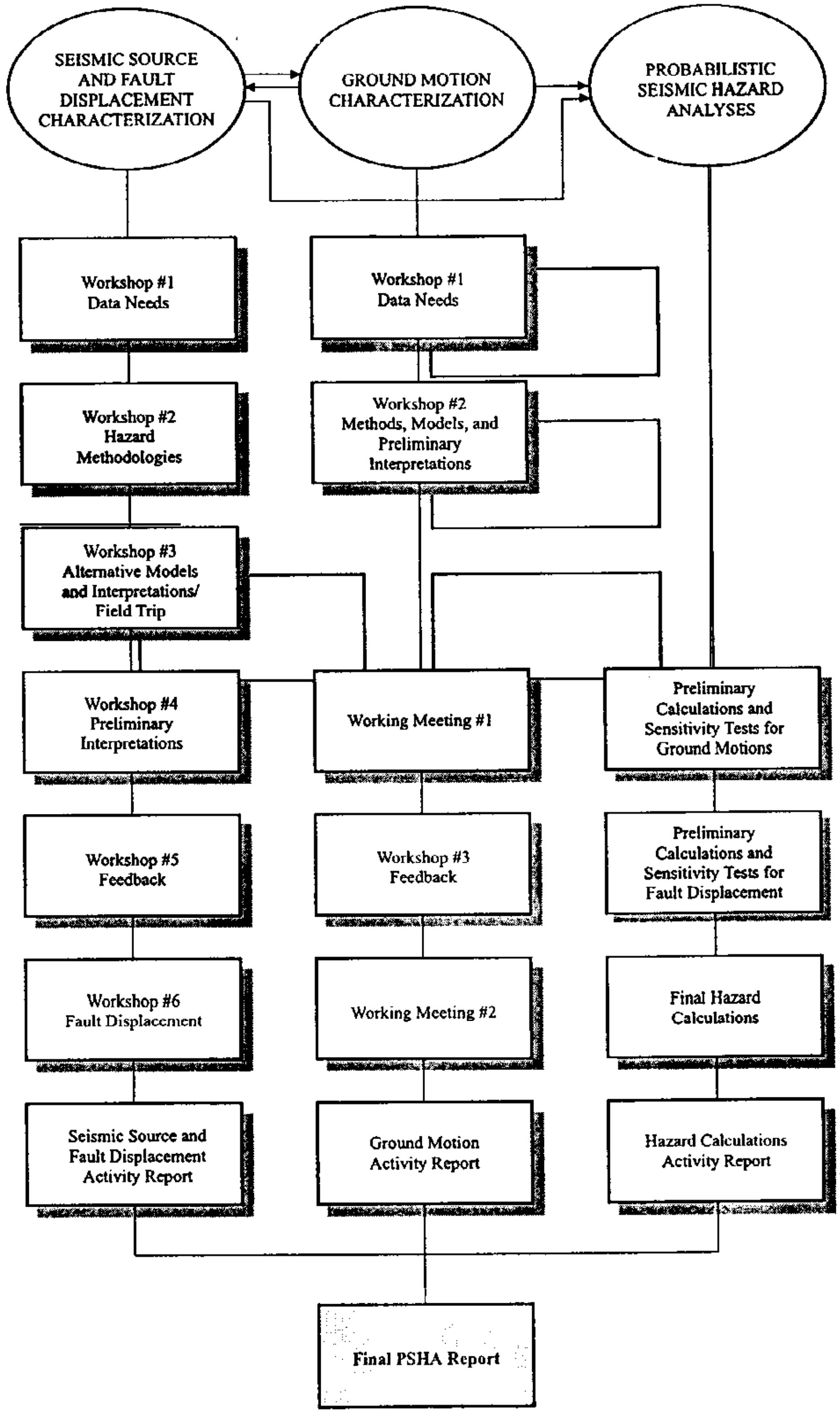


Source: CRWMS M&O 1998a, Appendix G

Note: Significant earthquakes are shown with the year of occurrence.

Figure 1. Historical Seismicity (1868 to 1996) Showing Mw 3.5 or Modified Mercalli Intensity III 01 Greater Events within 300 km of Yucca Mountain

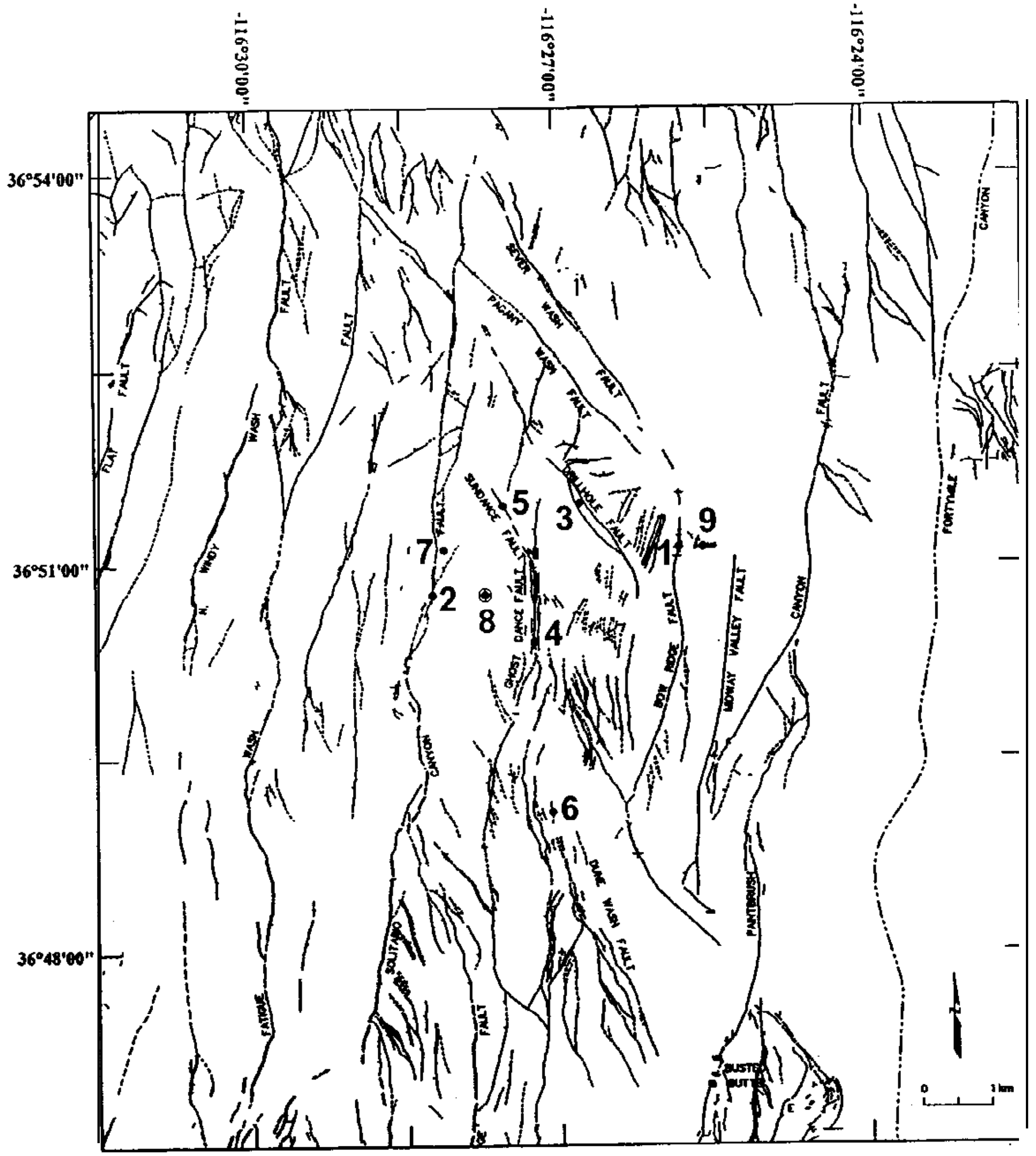
FI DB 4/21/00
67 of 89



Source: CRWMS M&O 1998a

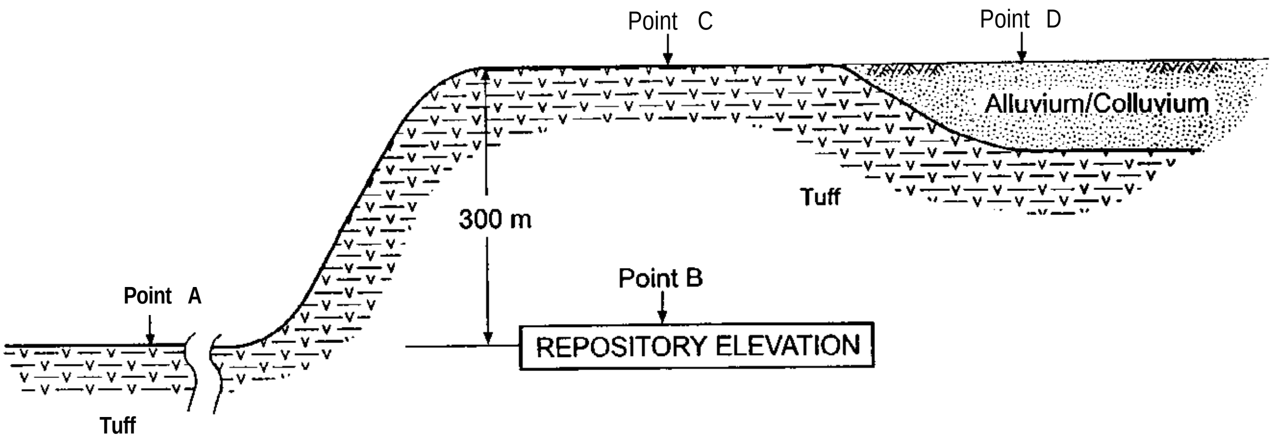
Note: The expert elicitation process was initiated after workshop #4 for the SSFD experts and after Working Meeting #1 for the GM experts.

Figure 2. Probabilistic Seismic Hazard Analyses Project Process for Yucca Mountain



Source: CRWMS M&O 1998a, Section 4
Note: See Figure 6 for regional location map.

Figure 3. Location of Nine Points for Demonstration of Fault Displacement Hazard Assessment (1 through 9) and Location of the Site for Ground Motion Hazard Assessment-(⊕ at Point 8)



LEGEND

Point A – Reference rock outcrop at repository elevation

Point B – Repository elevation

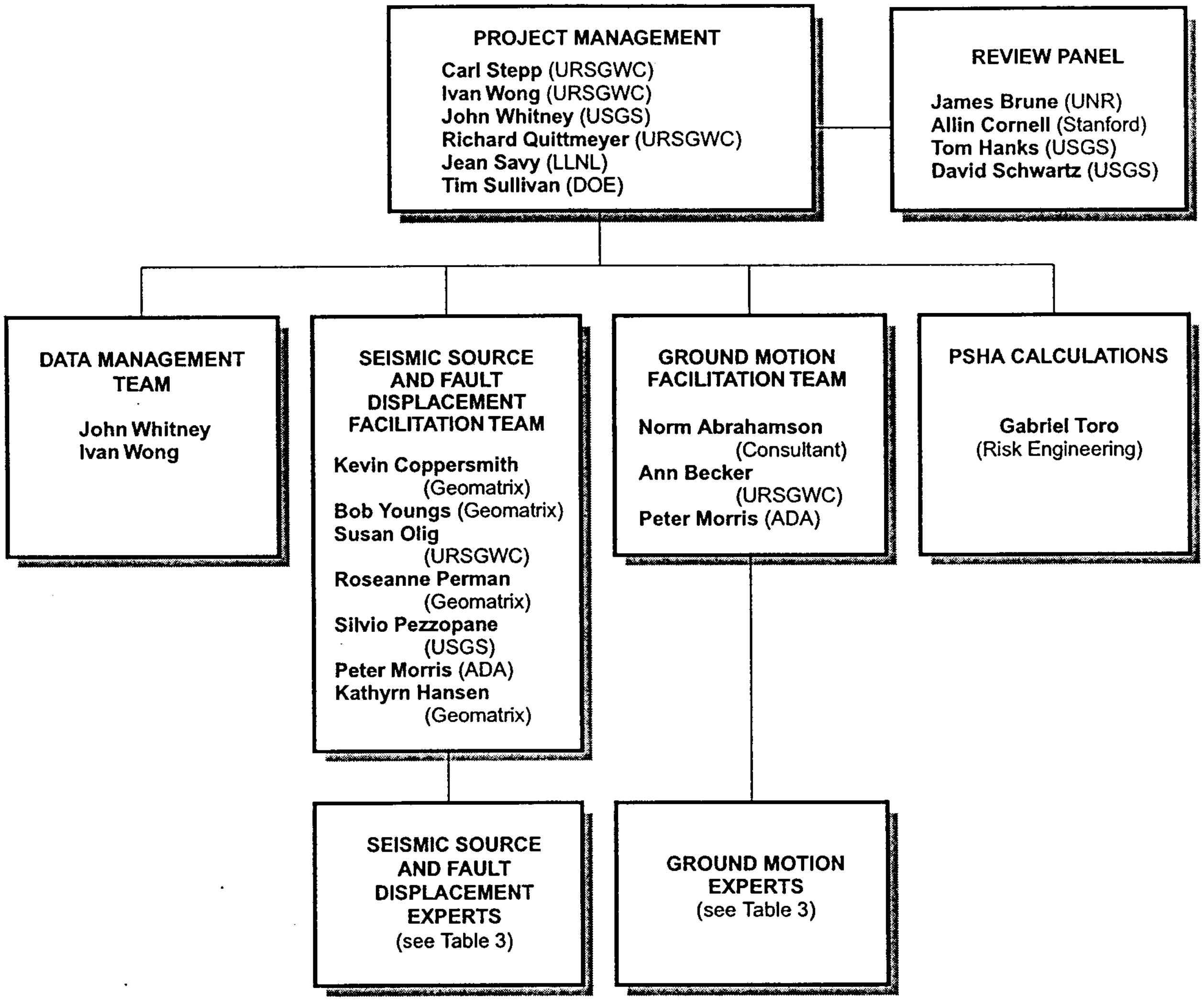
Point C – Rock surface

Point D-Soil surface

Source: CRWMS M&O 1998a, Section 1

Note: All of the PSHA ground motion calaculations discussed in this AMR were done for Point A. Point A is located near Point 8 on Figure 3. However. site conditions assumed for Point A do not correspond to actual conditions at Point 8, but were defined for reference conditions (discussed in Section 6.3.3.1.1) to facilitate future application of results to a variety of site conditions.

Figure 4. Locations of Specified Seismic Design Ground Motion input



ADA – Applied Decision Analysis

DOE – U.S. Department of Energy

LLNL – Lawrence Livermore National Laboratory

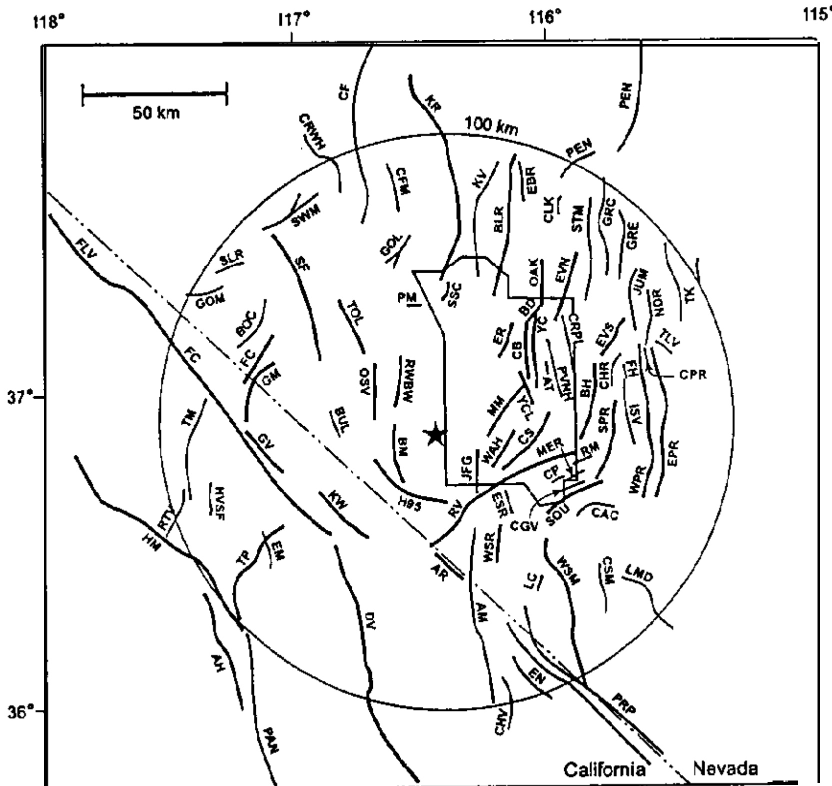
UNR – University of Nevada, Reno

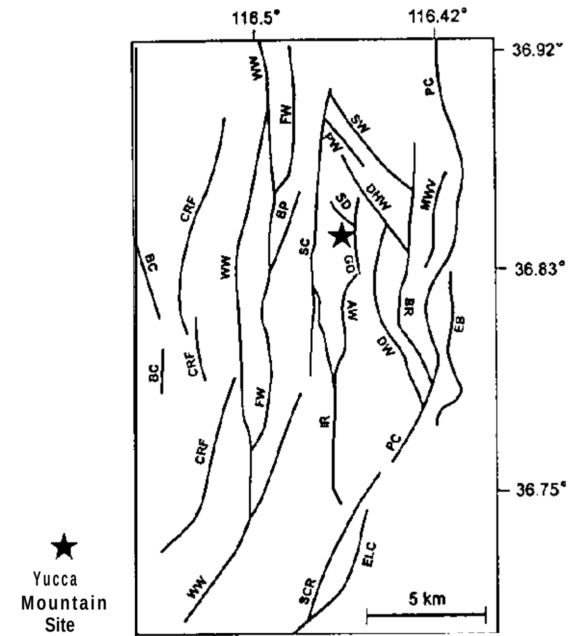
URSGWC – URS Greiner Woodward Clyde

USGS – U.S. Geological Survey

Source: CRWMS M&O 1998a, Section 1

Figure 5. PSHA Project Organization





AW* – Abandoned Wash
BC* – Black Cone
BP* – Boomerang Point
BR* – Bow Ridge
CRF* – Crater Flat
DHW* – Drill Hole wash
DW* – Dune wash
EB* – East Busted Butte
ELC* – East Lathrop Cone
FW* – Fatigue Wash
GD* – Ghost Dance
IR* – Iron Ridge
MWV* – Midway Valley
PW* – Pagany Wash
PC* – Paintbrush Canyon
SW* – Sever Wash
SC* – Solitario Canyon
SCR* – Stagecoach Road
SD* – Sundance
WW* – Windy Wash

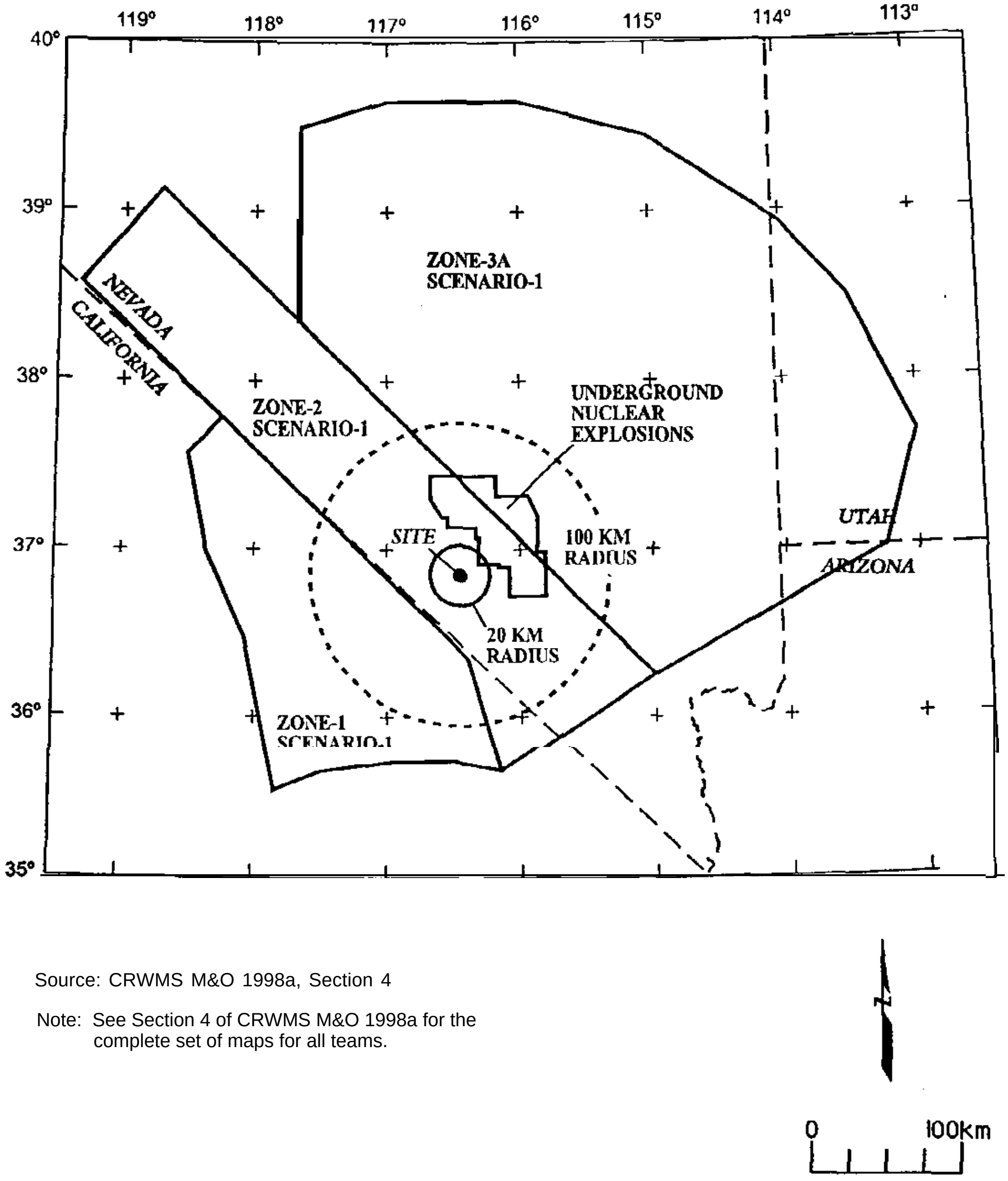
AR* – Amargosa River
AT – Area Three
AH* – Ash Hill
AM* – Ash Meadows
BM* – Bare Mountain
BLR* – Belted Range
BOC – Bonnie Claire
BD – Boundary
BUL – Bullfrog Hills
BH* – Buried Hills
CAF – Cactus Flat
CFM – Cactus Flat-Mellan
CRWH – Cactus Range-Wellington Hills
CAC – Cactus Springs
CS* – Cane Spring
CB* – Carpetbag
CPR – Central Pintwater Range
CSM – Central Spring Mountains
CLK – Chalk Mountain
CP – Checkpoint Pass
CHR – Chert Ridge
CHV – Chicago Valley
CRPL – Cockeyed Ridge-Papoose Lake
CGV – Crossgrain Valley
DV* – Death Valley
EBR – East Belted Range
EN* – East Nopah
EPR* – East Pintwater Range
ESR* – East Specter Range
ER* – Eleana Range
EM – Emigrant
EVN* – Emigrant Valley North
EVS* – Emigrant Valley South
FH – Fallout Hills
FLV* – Fish Lake Valley
FC* – Furnace Creek
GOL – Gold Flat
GOM – Gold Mountain
GV* – Grapevine
GM* – Grapevine Mountain
GRC – Groom Range Central
GRE – Groom Range East
HVSF – Hidden Valley-Sand Flat
H95* – Highway 95
HM* – Hunter Mountain
ISV – Indian Springs Valley
JFG* – Jackass Flats Gravity
JUM – Jumbled Hills
KR* – Kawich Range
KV – Kawich Valley
KW* – Keane Wonder
LMD – La Madre
LC – Last Chance Range
MER – Mercury Ridge
MM* – Mine Mountain
NDR – North Desert Range
OAK* – Oak Springs Butte
OSV* – Oasis Valley
PRP* – Pahrump
PM1* – Pahute Mesa
PAN* – Panamint Valley
PEN – Penoyer
PVNH – Plutonium Valley-North Halfpint Ridge
RTV – Race Track Valley
RM – Ranger Mountain
RV* – Rock Valley
RWBW* – Rocket Wash-Beatty Wash
SF* – Sarcobatus Flat
SLR – Slate Ridge
SOU* – South Ridge (includes Peace Camp)
SSC* – South Silent Canyon
SPR* – Spotted Range
SWM – Stonewall Mountain
STM – Stumble
TK – Tikaboo
TM – Tin Mountain
TOL* – Tolicha Peak
TP* – Towne Pass
TLV – Three Lakes Valley
WAH* – Wahmonie
WPR* – West Pintwater Range
WSR* – West Specter Range
WSM* – West Spring Mountains
YC* – Yucca (Yucca Butte)
YCL* – Yucca Lake

*Faults included in the PSHA (CRWMS M&O, 1998a) are shown as bold lines on the map.

Source: Modified from CRWMS M&O 1998b, section 12.3

Figure 6. Known or Suspected Quaternary Faults and Potentially Significant Local Faults within 100 km of Yucca Mountain

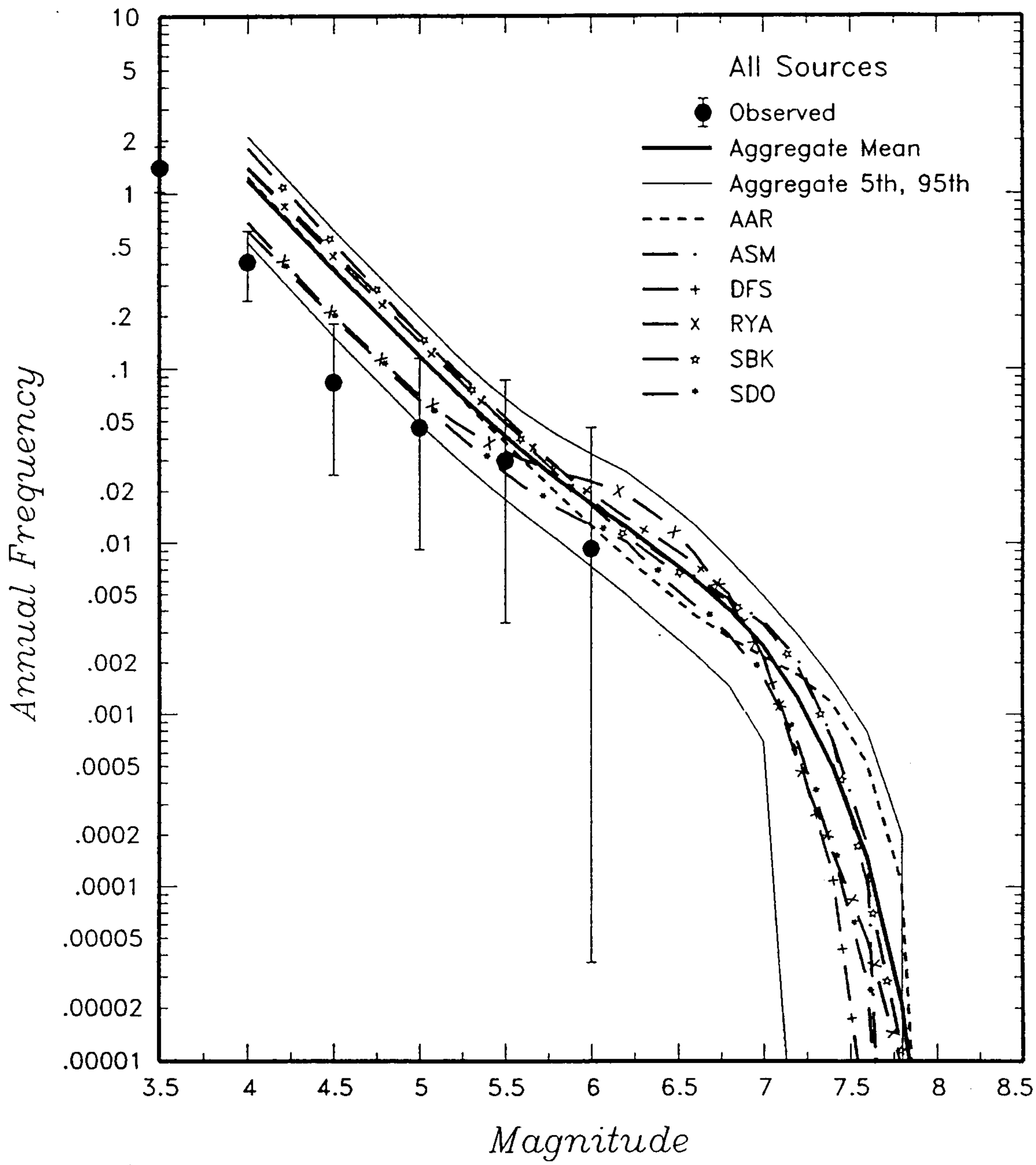
72 of 89



Source: CRWMS M&O 1998a, Section 4

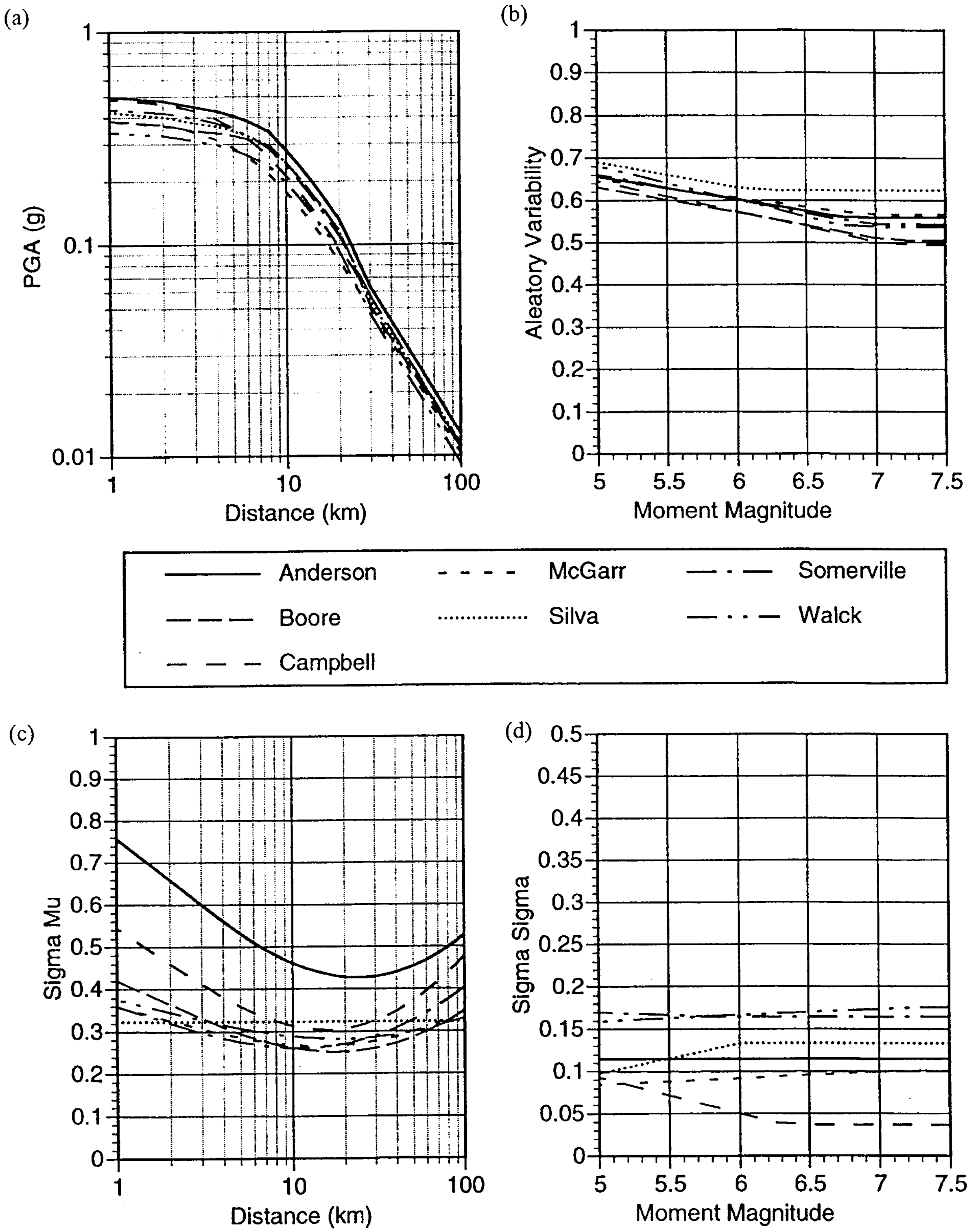
Note: See Section 4 of CRWMS M&O 1998a for the complete set of maps for all teams.

Figure 7. Map Showing One Scenario of an Example Regional Source Zone Model Considered by One SSFD Expert Team



Source: CRWMS M&O 1998a, Section 4
Note: See Table 3 for explanation of team abbreviations.

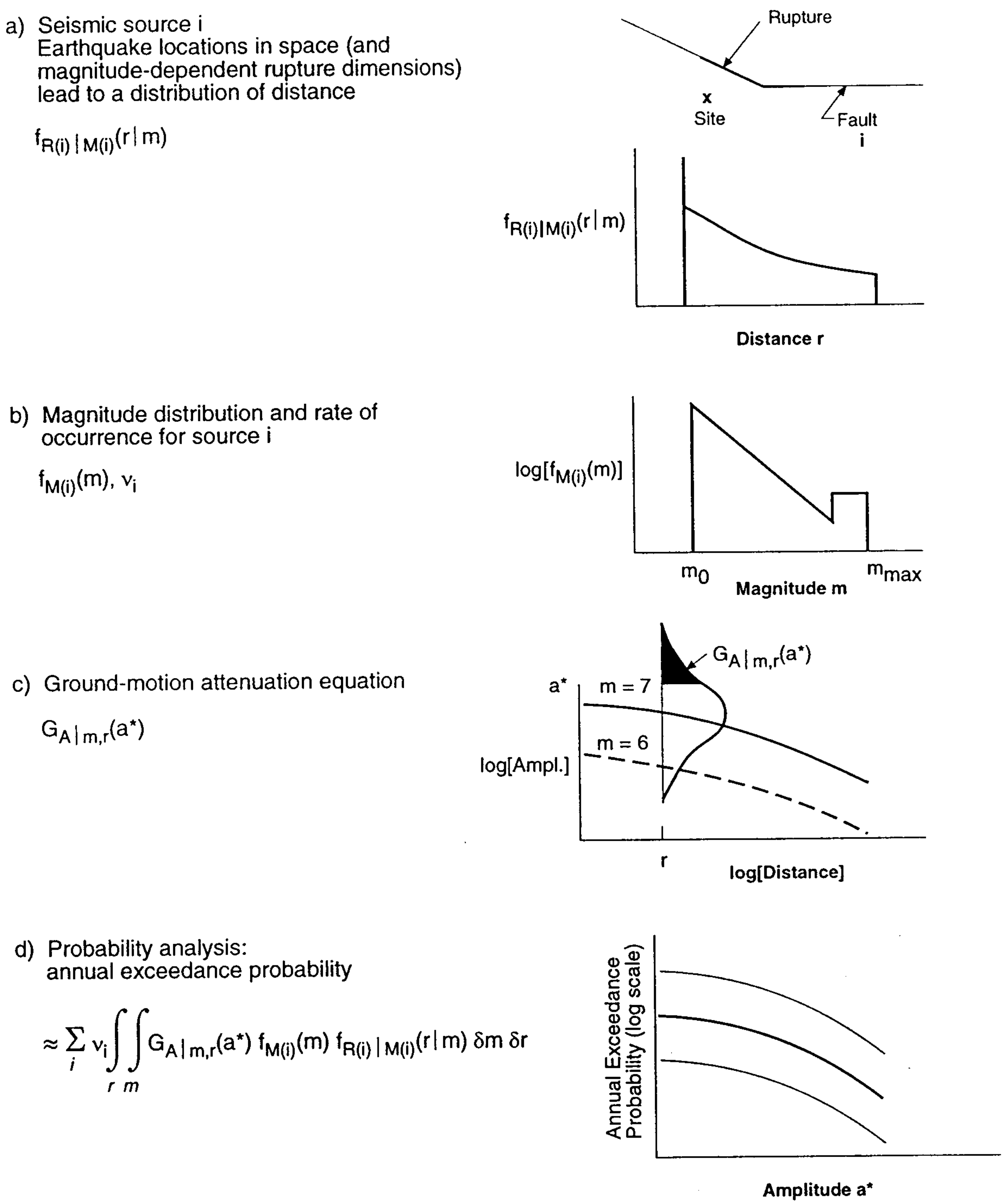
Figure 8. Predicted Mean, 5th, and 95th-Percentile Recurrence Rates for All Sources Combined Within 100 km of the Site for all SSFID Expert Teams Compared to Mean Recurrence Estimates for Individual Teams



Source: CRWMS M&O 1998a, Section 6

Note: (a) median attenuation of horizontal PGA, (b) aleatory uncertainty of the median values, (c) epistemic variability, and (d) epistemic uncertainty in the aleatory variability.

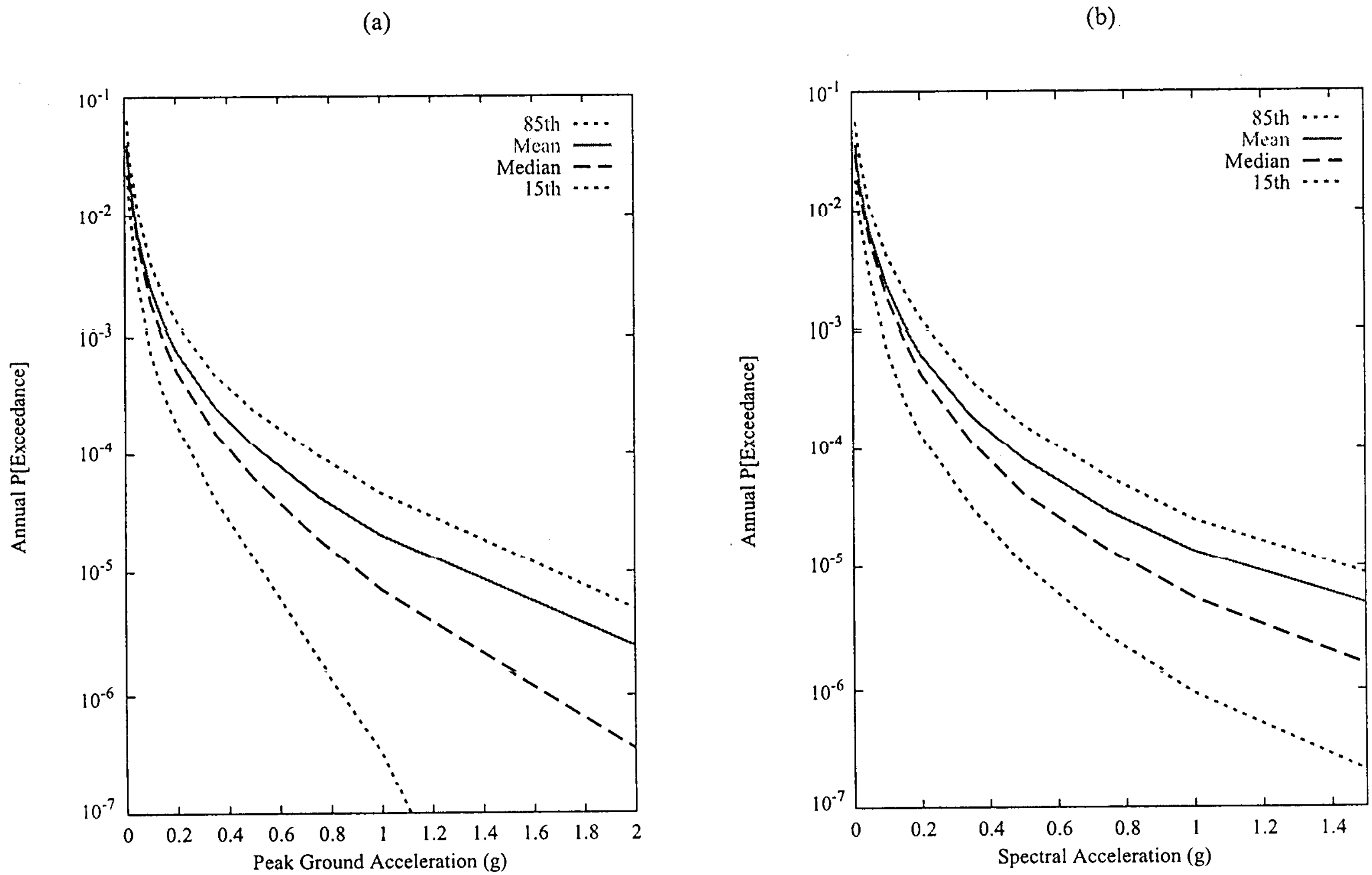
Figure 9. PGA Characterization of a M_w 6.5 Normal Faulting Earthquake in the Hanging Wall



Source: CRWMS M&O 1998a, Section 7

Figure 10. Seismic Hazard Computational Model

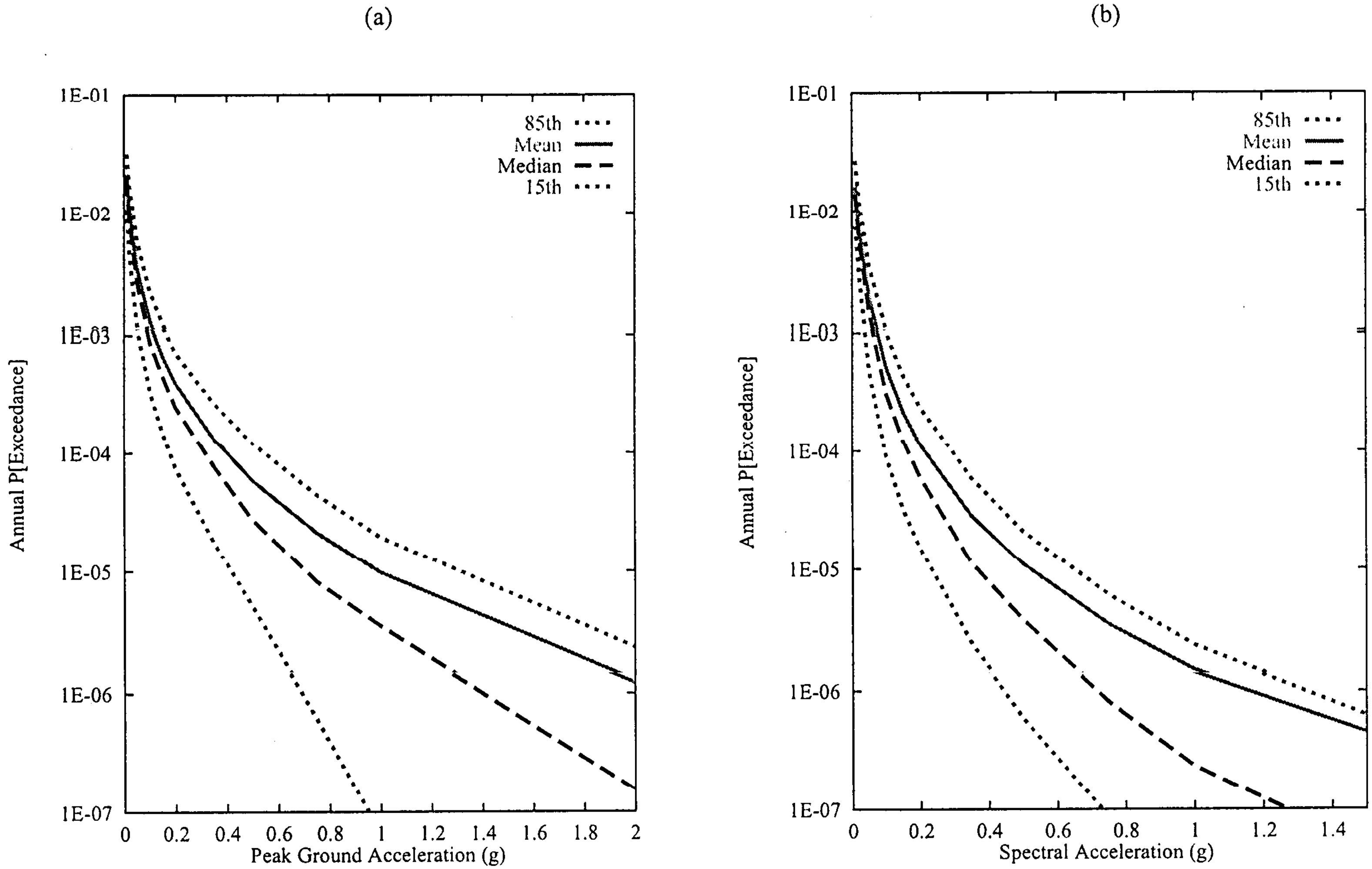
EH DSB 4/27/00
77 of 89



Source: CRWMS M&O 1998a, Section 7

Note: All ground motion results are calculated for the reference rock outcrop (Point A on Figure 4).

Figure 11. Summary Hazard Curves for Horizontal (a) PGA and (b) 1-Hz SA

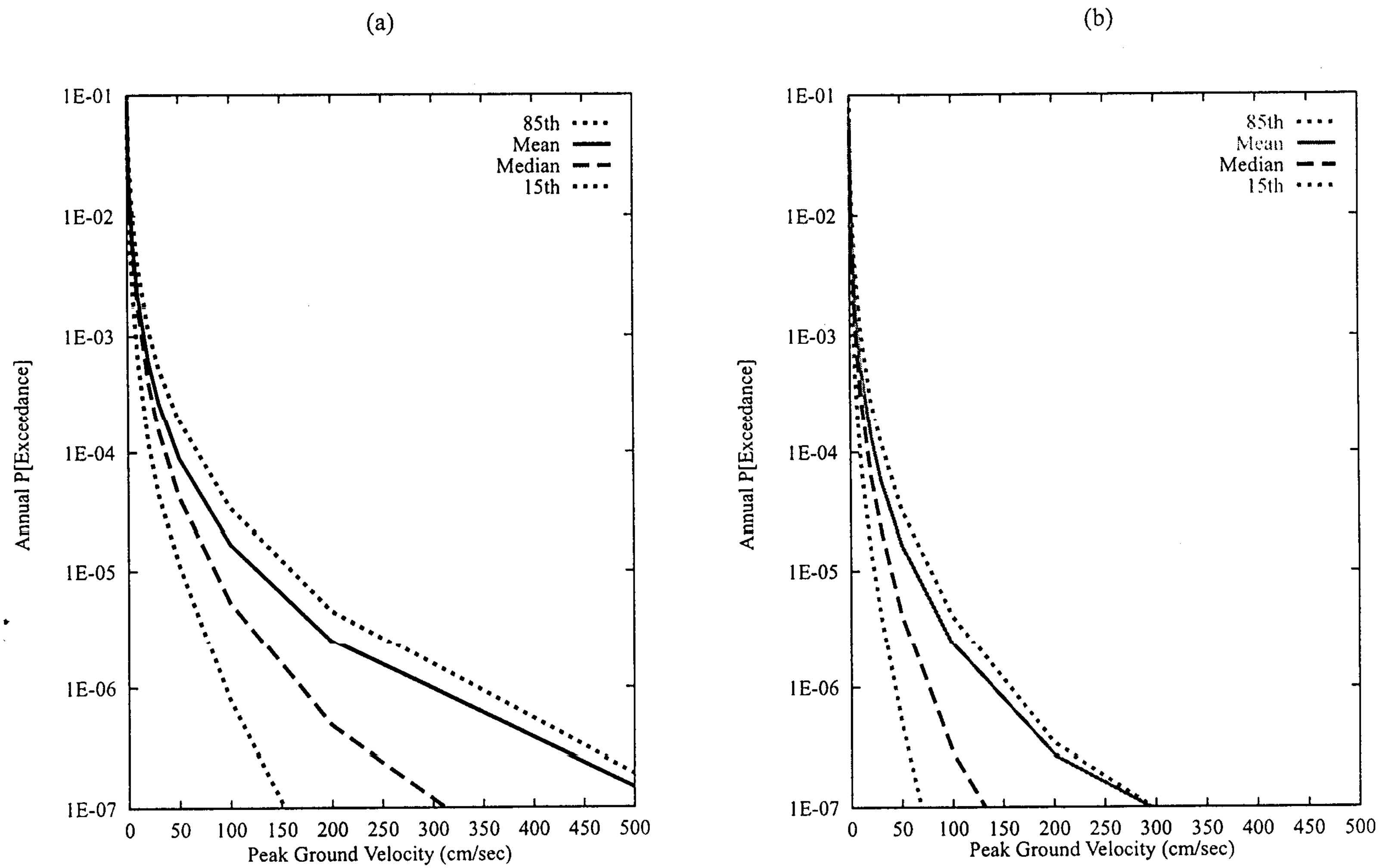


Source: CRWMS M&O 1998a, Section 7

Note: All ground motion results are calculated for the reference rock outcrop (Point A on Figure 4).

Figure 12. Summary Hazard Curves for Vertical (a) PGA and (b) I-Hz SA

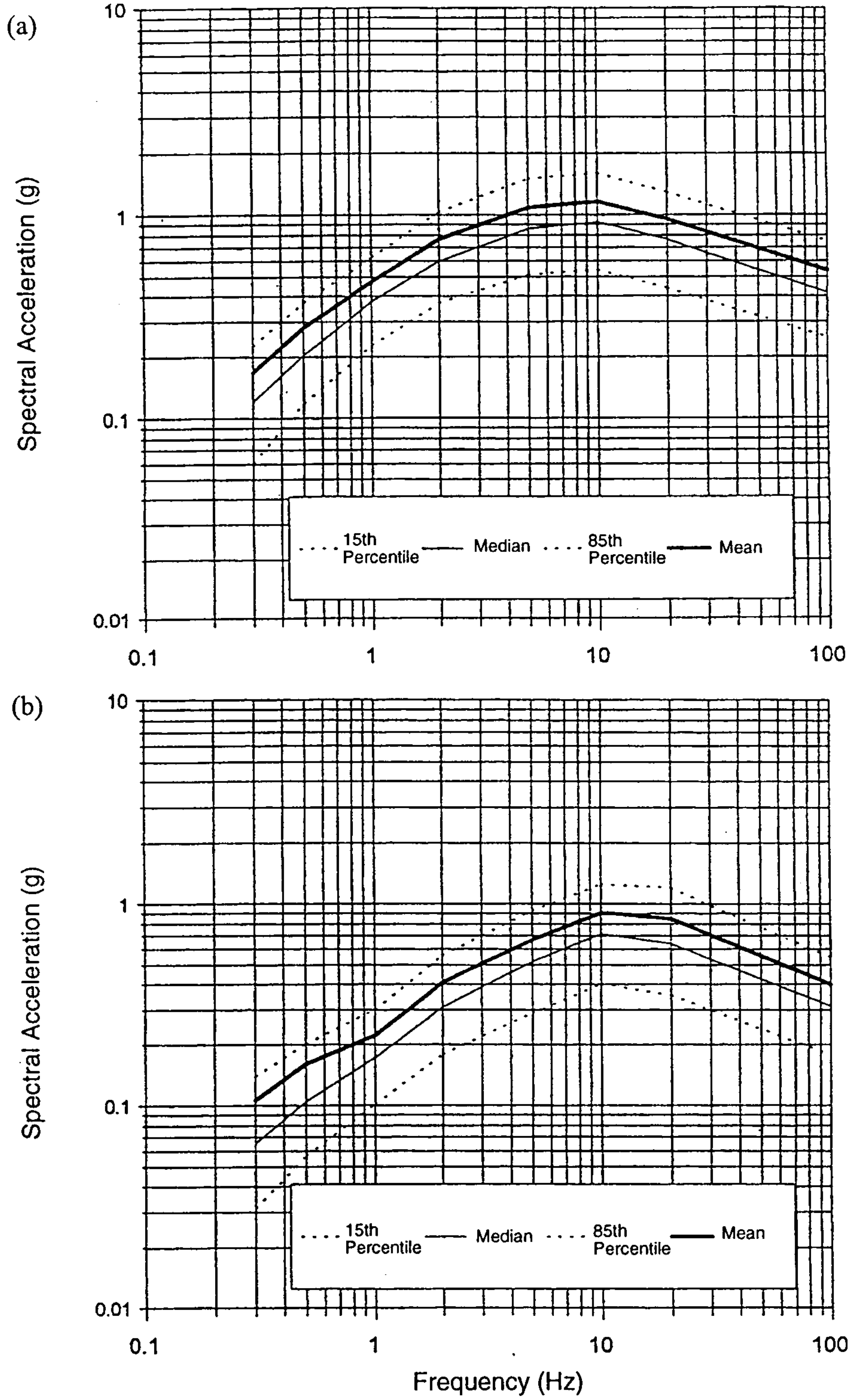
79 of 89



Source: CRWMS M&O 1998a, Section 7

Note: All ground motion results are calculated for the reference rock outcrop (Point A on Figure 4).

Figure 13. Summary Hazard Curves for (a) Horizontal and (b) Vertical PGVs

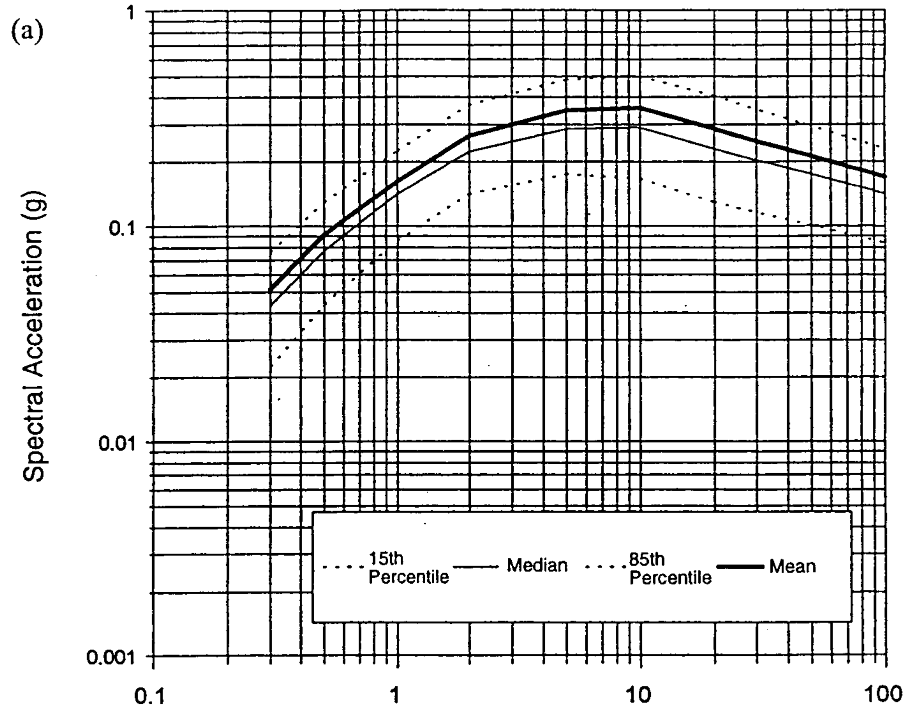


Source: DTN: MO0002MWDRIFM3.001

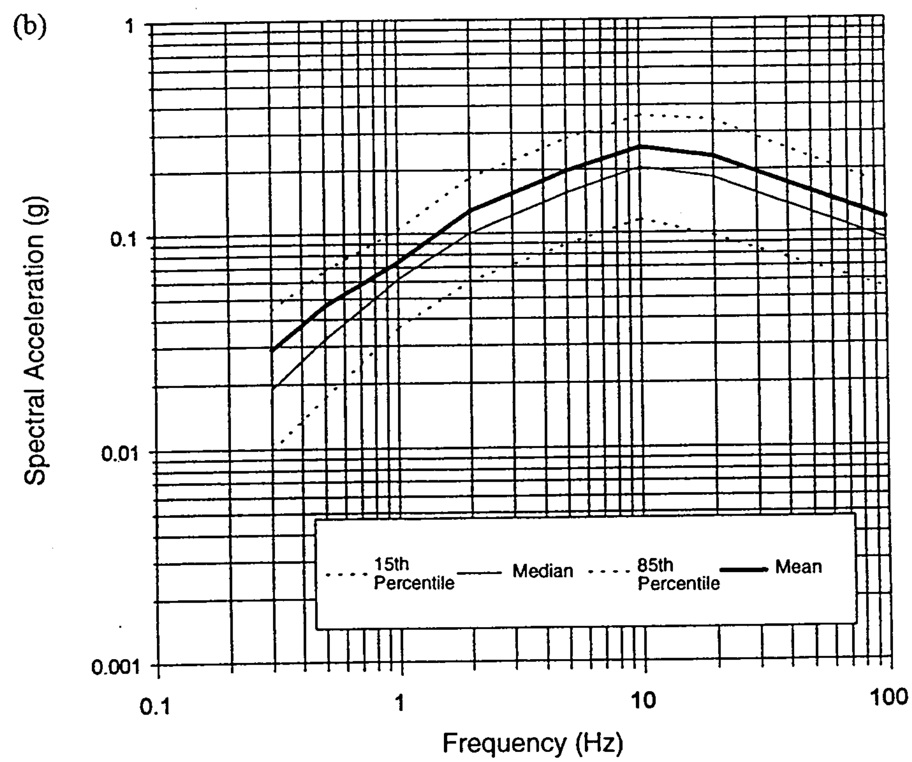
Note: All ground motion results are calculated for the reference rock outcrop (Point A on Figure 4).

Figure 14. Horizontal (a) and Vertical (b) Uniform Hazard Spectra for 10^{-4} Annual Exceedance Probability

(a)



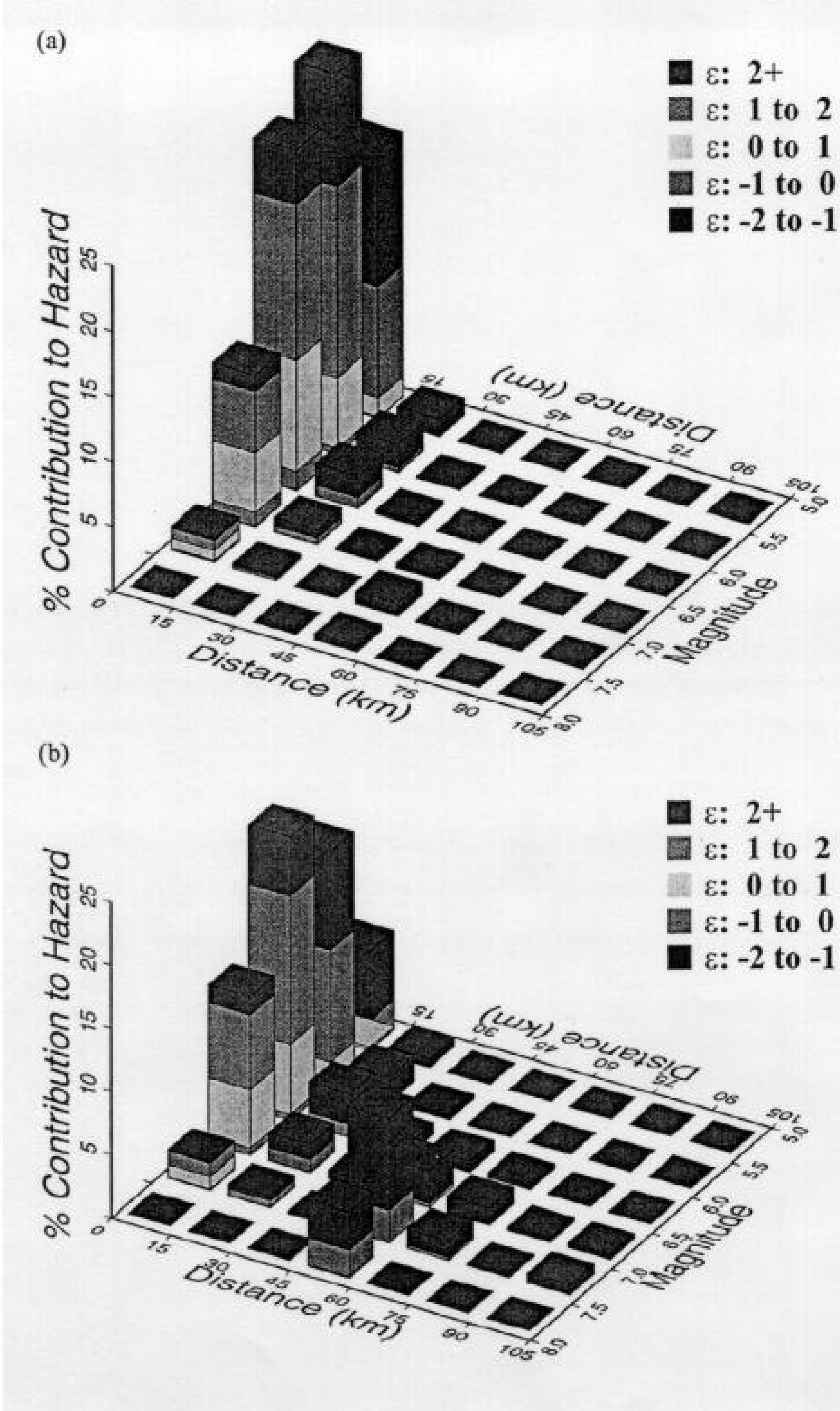
(b)



Source: DTN: MO0002MWDRIFM3.001

Note: All ground motion results are calculated for the reference rock outcrop (Point A on Figure 4).

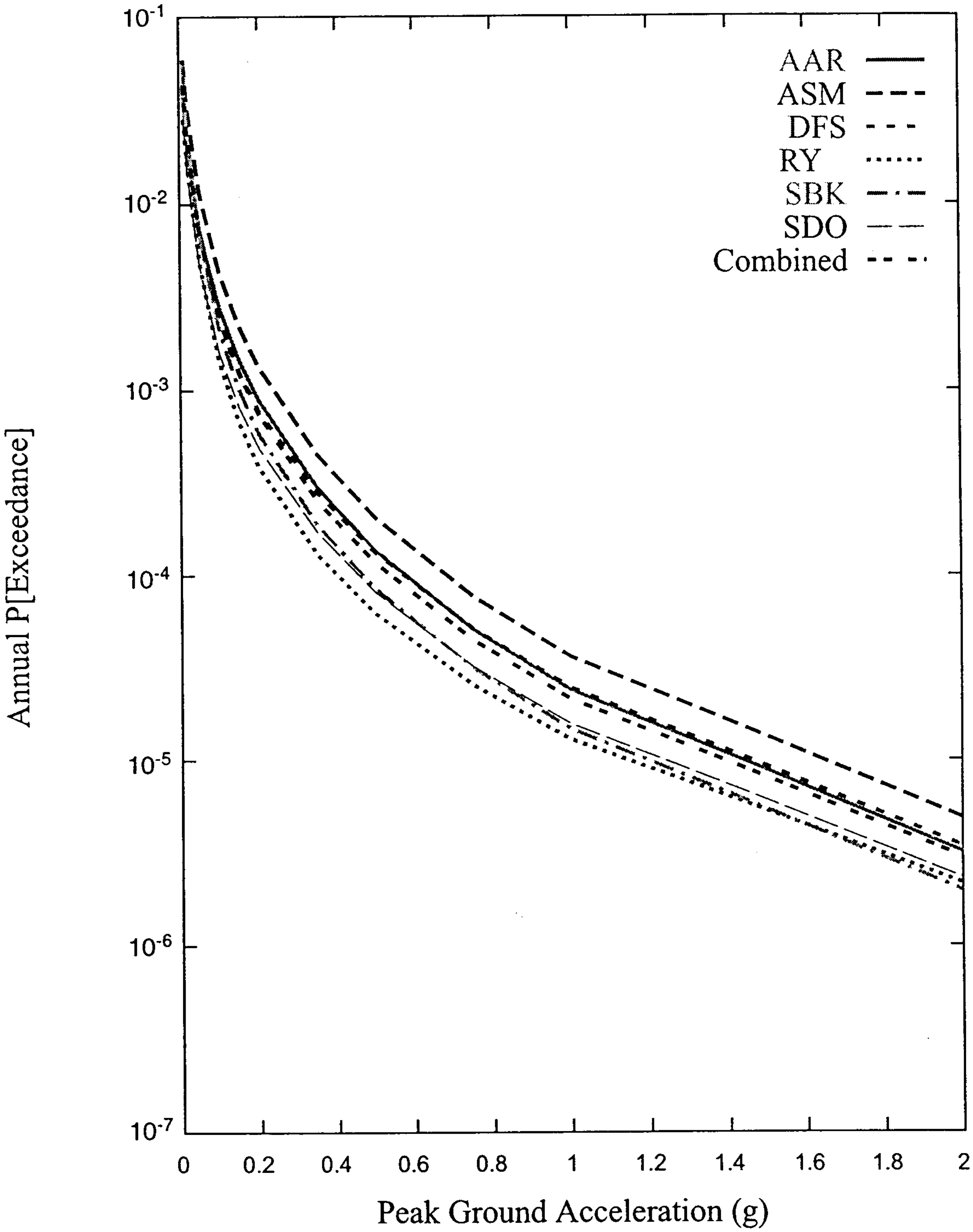
Figure 15. Horizontal (a) and Vertical (b) Uniform Hazard Spectra for 10^{-3} Annual Exceedance Probability



Source: CRWMS M&O 1998a, Section 7

Note: Both plots are for 10^{-4} annual exceedance probability.

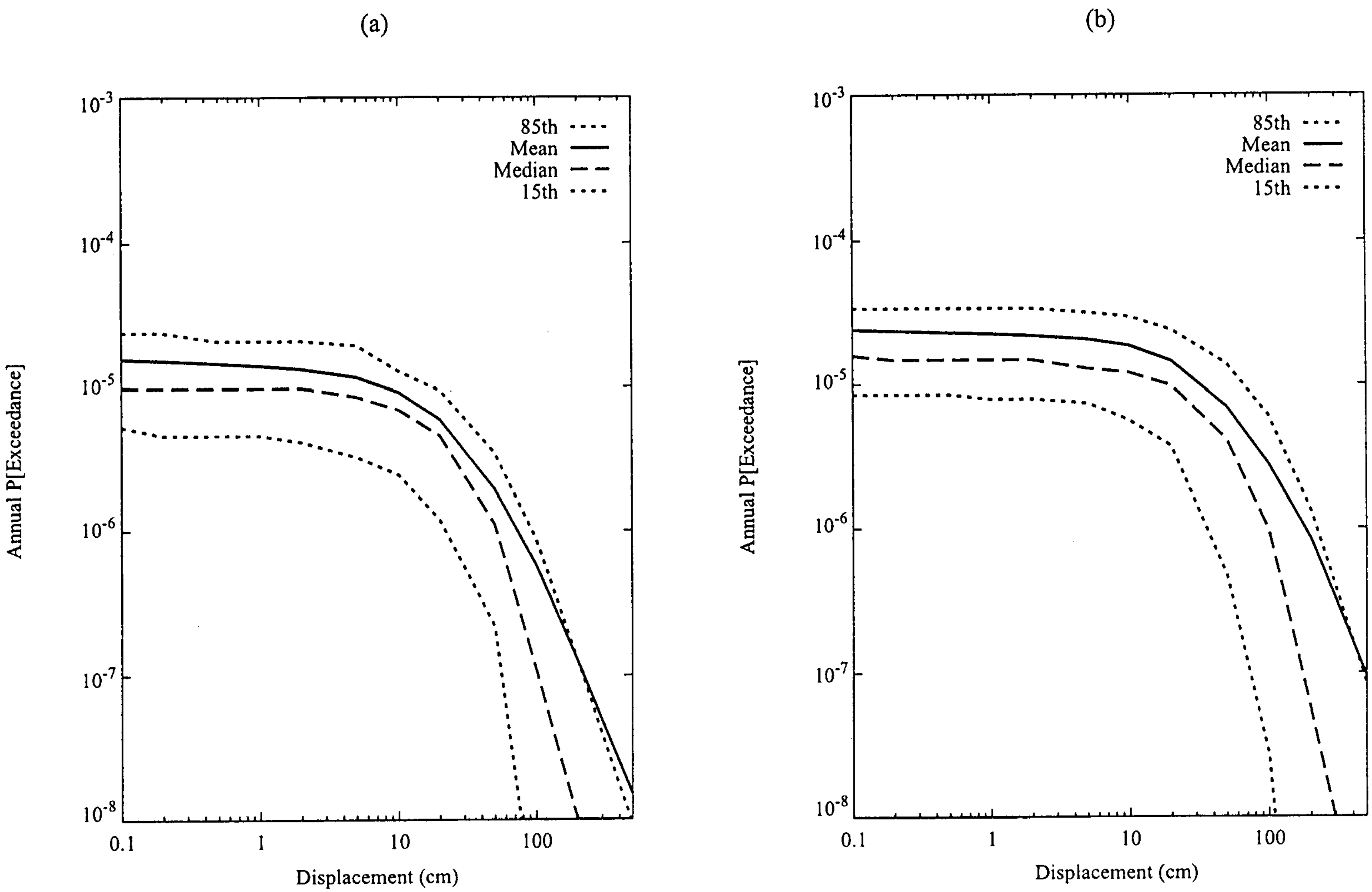
Figure 16. Magnitude-Distance-Epsilon (ε) Deaggregation of Mean Seismic Hazard for (a) 5 to 10 Hz and (b) 1 to 2 Hz Horizontal SA



Source: CRWMS M&O 1998a, Section 7

Note: See Table 3 for explanation of team abbreviations. All ground motion results are calculated for the reference outcrop (Point A on Figure 4).

Figure 17. Mean Hazard Curves by Tearn for Horizontal PGA

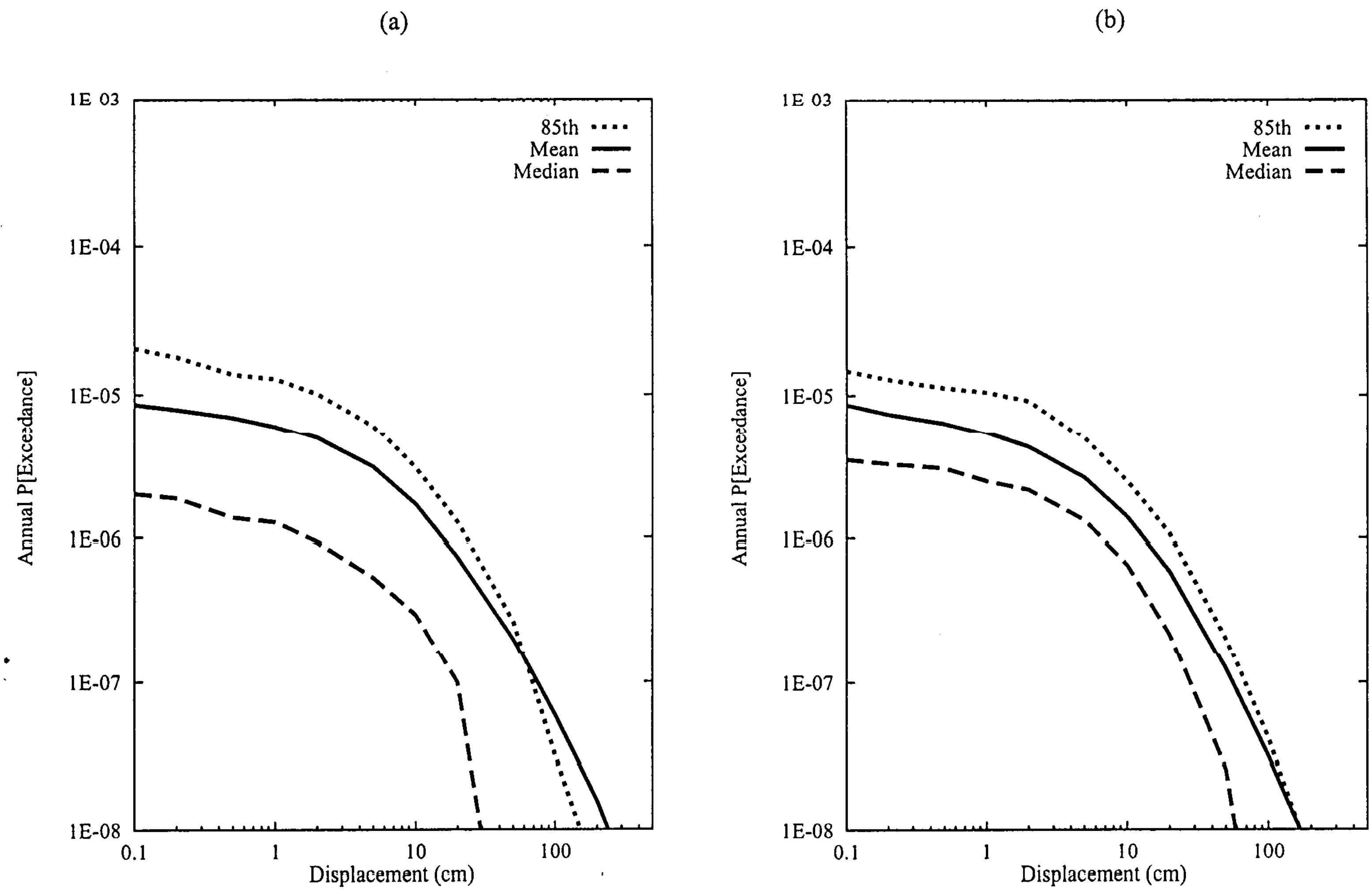


Source: CRWMS M&O 1998a, Section 8
Note: See Figure 3 for site locations.

Figure 18. Summary Fault Displacement Hazard Curves for (a) Site 1, Bow Ridge Fault and (b) Site 2, Solitario Canyon Fault

84 of 89

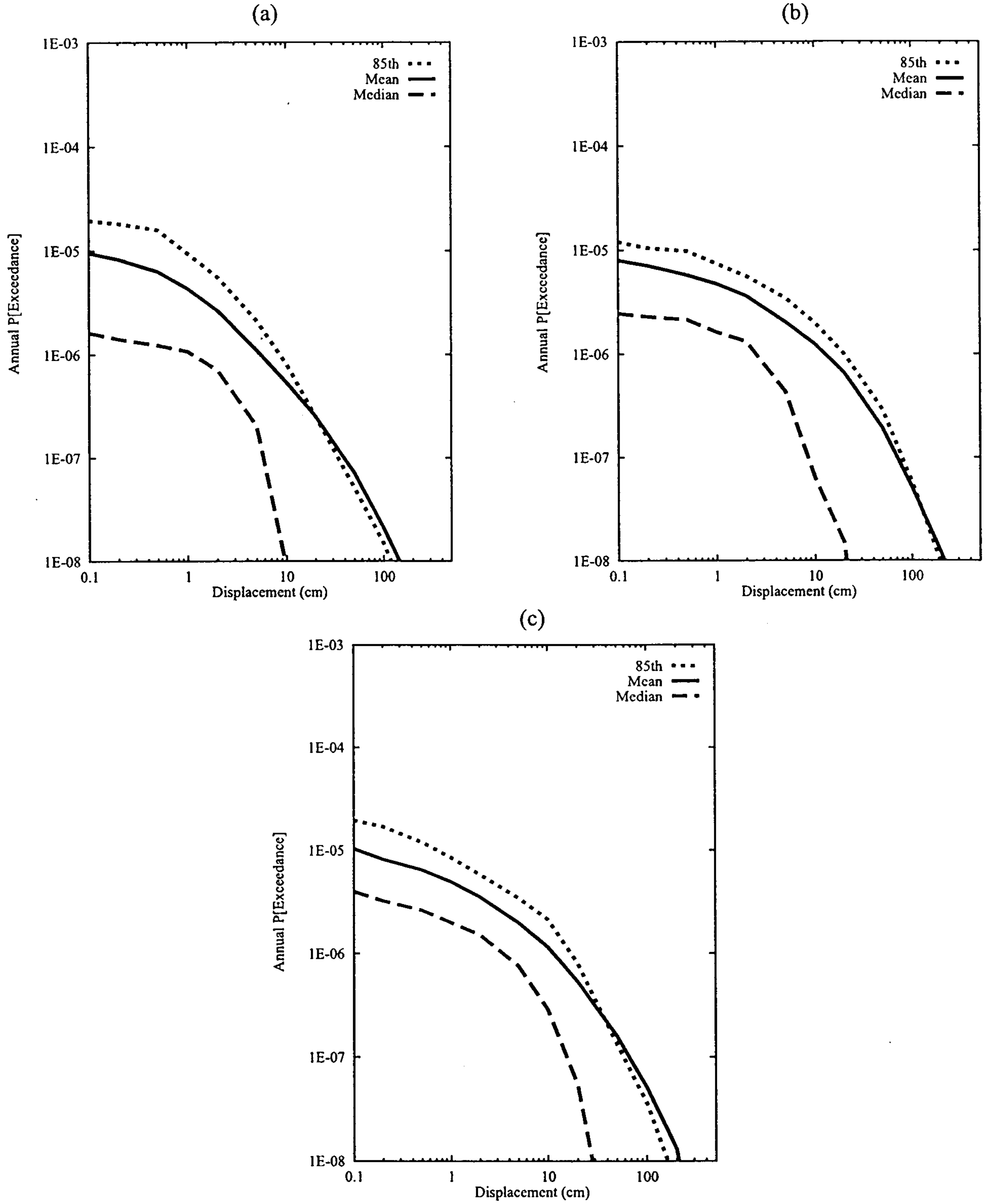
Fig DS18 4/27/00
85 of 89



Source: CRWMS M&O 1998a, Section 8

Note: The 15th percentile curve lies below the range of displacements plotted for both sites.

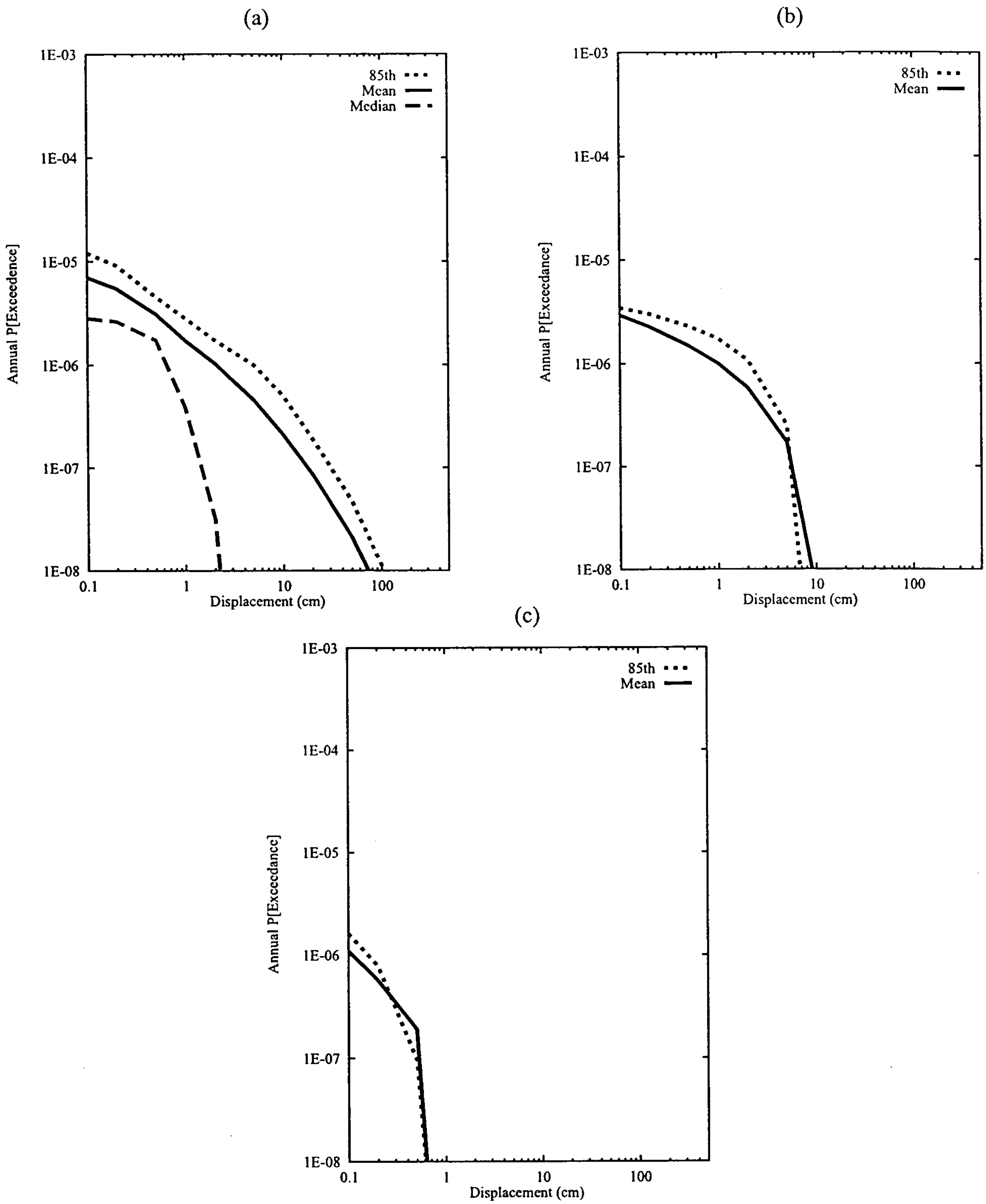
Figure 19. Summary Fault Displacement Hazard Curves for (a) Site 3, Drill Hole Wash Fault and (b) Site 4, Ghost Dance Fault



Source: CRWMS M&O 1998a, Section 8

Note: The 15th percentile curve lies below the range of displacements plotted for both sites.

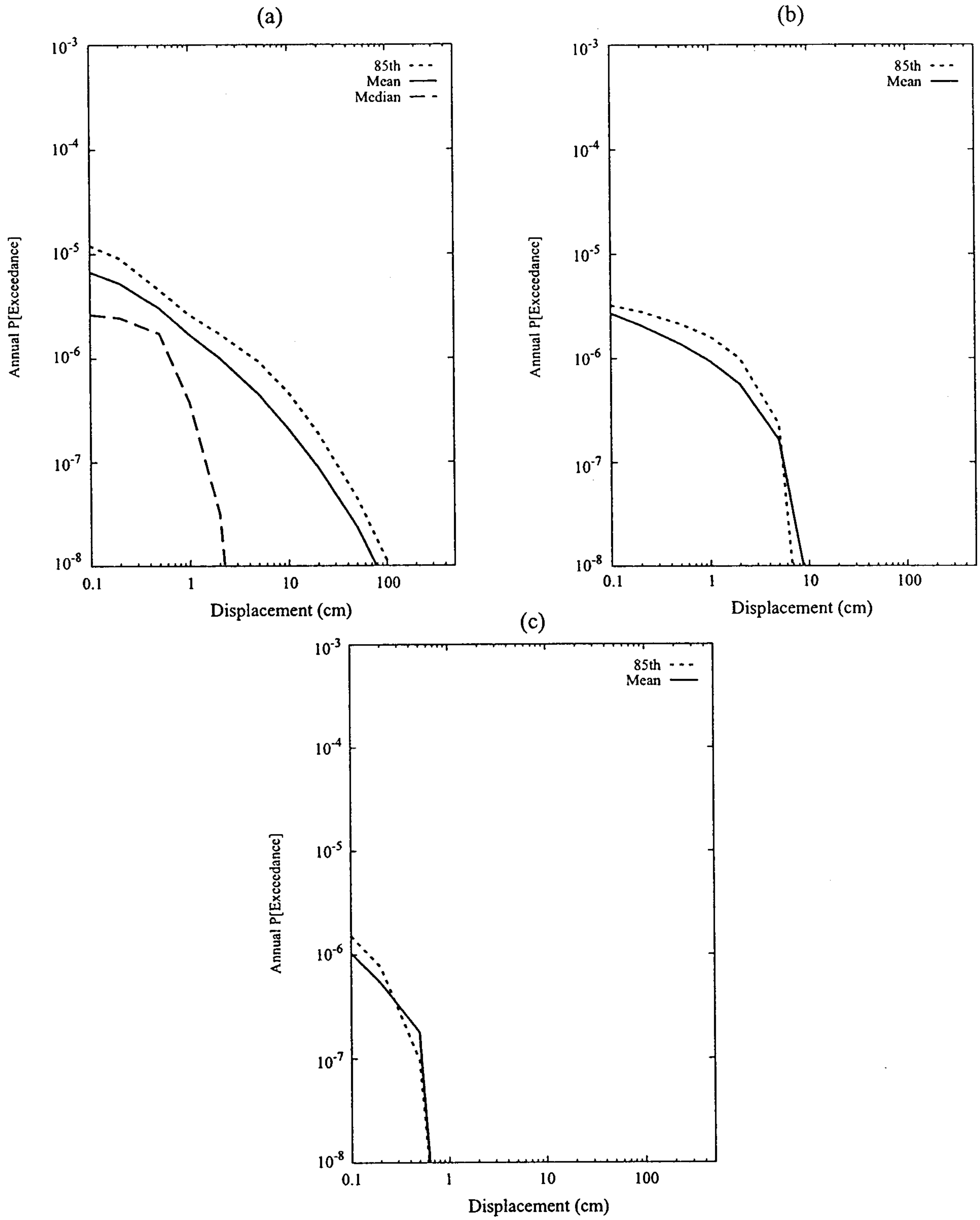
Figure 20. Summary Fault Displacement Hazard Curves for (a) Site 5, Sundance Fault (b) Site 6, Unnamed Fault West of Dune Wash, and (c) Site 9, Midway Valley



Source: CRWMS M&O 1998a, Section 8

Note: The 15th percentile curve lies below the range shown for all conditions and the median lies below the range shown for Plots b and c. See Figure 3 for site location.

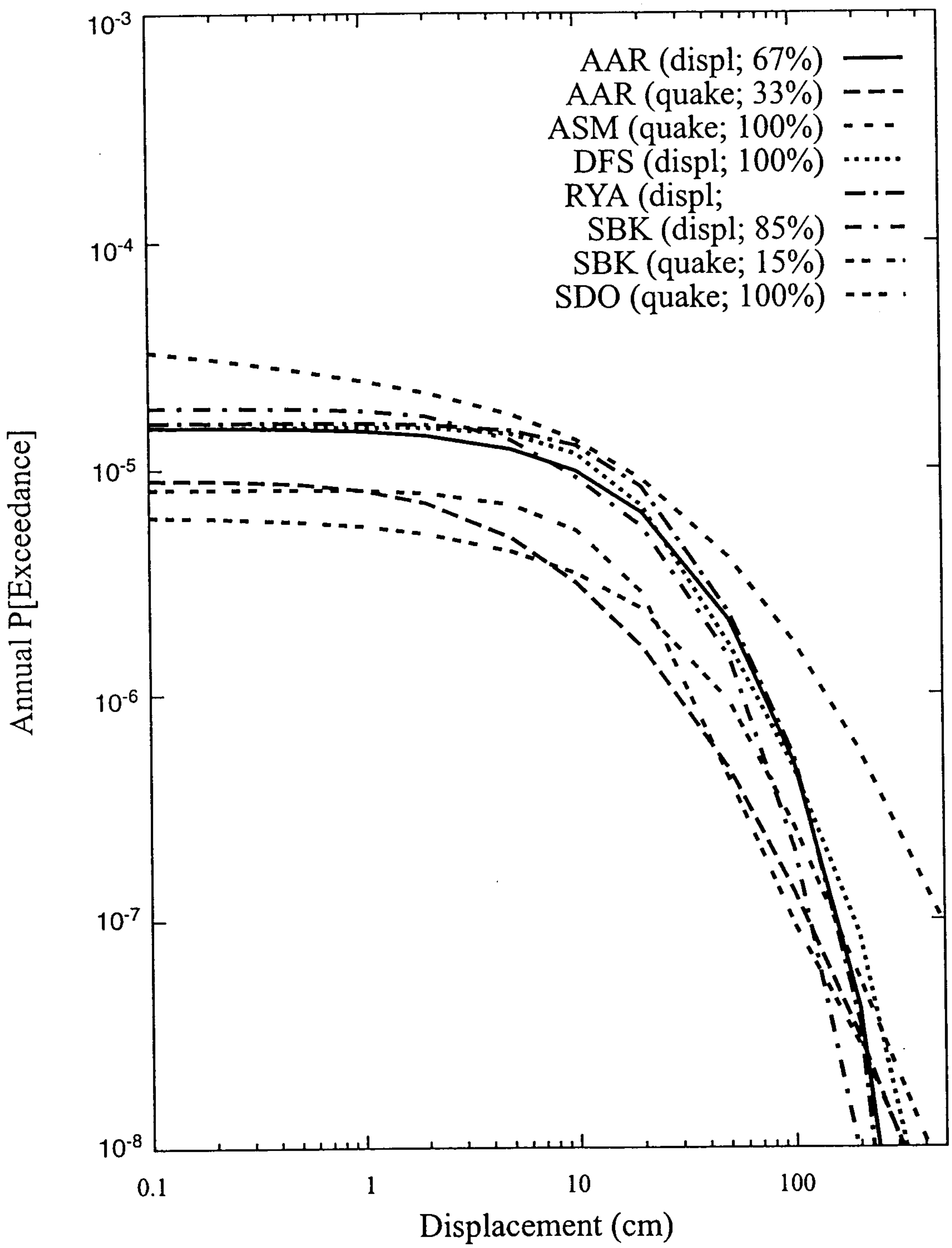
Figure 21. Summary Fault Displacement Hazard Curves for Site 7, Considering Three Hypothetical Conditions: (a) 2 m of Cumulative Displacement, (b) 10 cm of Cumulative Displacement, and (c) No Measurable Cumulative Displacement



Source: CRWMS M&O 1998a, Section 8

Note: The 15th percentile curve lies below the range shown for all conditions and the median lies below the range shown for Plots b and c. See Figure 3 for site location.

Figure 22. Summary Fault Displacement Hazard CuNqs for Site 8, Considering Three Hypothetical Conditions: (a) 2 m of Cumulative Displacement (b) 10 cm of Cumulative Displacement, and (c) No Measurable Cumulative Displacement



Source: CRWMS M&O 1998a, Section 8

Note: See Table 3 for explanation of team abbreviations.

Figure 23. Mean Fault Displacement Hazard Curves by Team for Site 1, Bow Ridge Fault

ATTACHMENT I
GLOSSARY

GLOSSARY

Aleatory uncertainty – Refers to randomness in a physical process. This uncertainty cannot be reduced with additional data.

Anastamosing – Interconnecting parts between any branching system, applied here to faults.

Annual exceedance probability – The probability that a specified value (such as for ground motions or fault displacement) will be exceeded during 1 year.

Attenuation - A decrease in seismic-signal amplitude as waves propagate from the seismic source. Attenuation is caused by geometric spreading of seismic-wave energy and by the absorption and scattering of seismic energy in different earth materials (termed anelastic attenuation).

Earthquake recurrence model – A model for the rate of occurrence of different size earthquakes, usually expressed as a relation between earthquake magnitude and the annual frequency of occurrence of earthquakes of that magnitude and larger. Examples include exponential, truncated exponential, characteristic, and maximum-magnitude models.

Deaggregate – To break apart a whole into its constituent parts.

Dip-slip fault – A fault in which the relative displacement is along the direction of dip of the fault plane and the largest component of slip is usually vertical; the offset is either normal or reverse.

Distributed faulting – Secondary slip that occurs on faults or fractures in the vicinity of the principal rupture in response to the principal displacement.

Earthquake hazard - Any physical phenomenon associated with an earthquake that may produce adverse effects on human activities. These phenomena include surface faulting, ground shaking, landslides, liquefaction, tectonic deformation, tsunami, and seiche and their effects on land use, man-made structures, and socioeconomic systems. A commonly used restricted definition of earthquake hazard is the probability of occurrence or exceedance of a specified level of ground shaking in a specified period of time.

Earthquake (or seismic) source – Geologic structure or feature (such as a fault or volcanic feature) that is a potential source for generating earthquakes.

Epistemic uncertainty – Uncertainty due to a lack of knowledge that can be reduced by additional data.

Epsilon (ε) – Ground motion parameter, epsilon, refers to the ground motion residual.

Footwall – The block of earth below an inclined fault (cf. hanging wall).

Free-field – Refers to ground motions that are not influenced by manmade structures.

Frequency (for seismic waves) – Number of cycles occurring in a unit of time. Hertz (Hz), the unit of frequency, is equal to the number of cycles per second.

Ground motion (shaking) - General term referring to the qualitative or quantitative aspects of movement of the earth's surface from earthquakes or explosions. Ground motion is produced by waves that are generated by sudden slip on a fault or sudden pressure at the explosive source and travel through the earth and along its surface.

Hanging wall – The block of earth above an inclined fault (cf. footwall).

Kappa – A parameter that quantifies the attenuation of ground motions in the near surface (< 1 to 2 km depth).

Left-lateral fault - A strike-slip fault on which the displacement of the far block is to the left when viewed from either side.

Magnitude (M)- A measure of earthquake size, determined by taking the common logarithm (base 10) of the largest ground motion recorded by a seismograph and applying a correction for the distance to the earthquake. Several scales have been defined, but the most commonly used are (1) local magnitude (M_L), commonly referred to as "Richter magnitude," (2) surface-wave magnitude (M_S), (3) body-wave magnitude (m_b), and (4) moment magnitude ($\boldsymbol{M}_{\mathbf{W}}$). Scales 1-3 have limited range and applicability and do not satisfactorily measure the size of the largest earthquakes. The moment magnitude ($\boldsymbol{M}_{\mathbf{W}}$) scale, based on the concept of **seismic moment**, is uniformly applicable to all sizes of earthquakes but is more difficult to compute than the other types. In principle, all magnitude scales could be cross calibrated to yield the same value for any given earthquake, but this expectation has proven to be only approximately true, thus the need to specify the magnitude type as well as its value.

Maximum magnitude – The largest magnitude considered reasonable for an earthquake source.

Normal fault - A dip-slip fault in which the rock above the fault plane has moved downward relative to the rock below.

Oblique-slip fault - A fault that combines some strike-slip motion with some dip-slip motion.

Period - Inverse of frequency, the time interval required for one full cycle of a wave.

Principal faulting – Slip that occurs along a main fault plane or planes that is (are) the locus for release of seismic energy (cf. distributed faulting).

Recurrence interval – The time span between earthquakes at a particular site.

Response spectrum – A curve showing the mathematically computed maximum response of a set of single damped harmonic oscillators of different natural frequencies to a given input ground-acceleration record.

Right-lateral fault - A strike-slip fault on which the displacement of the far block is to the right when viewed from either side.

Seismic moment - A measure of earthquake size that equals the product of the rupture-plane area, the average slip over that plane, and the rigidity (shear modulus) of the rock (cf. magnitude).

Seismic source parameters – Parameters that physically define an earthquake source, such as earthquake magnitude, location, orientation and geometry of a fault, stress drop, slip direction.

Shear wave – A seismic wave that involves a shearing motion in a direction perpendicular to the direction of propagation. Shear waves are the primary source of damaging ground motions within ~100 km of an earthquake.

Slip rate (SR) – The average rate of displacement at a point along a fault as determined from geodetic measurements, from offset manmade structures, or from offset geologic features whose age can be estimated. It is measured parallel to the predominant slip direction or estimated from the vertical or horizontal separation of geologic markers. Slip rates can be calculated by dividing displacement by recurrence intervals (and so slip rates can vary depending on the time period of interest).

Spectrum - In seismology, a curve showing amplitude and phase as a function of structural frequency or period (plural - spectra).

Stress drop - The difference between the stress across a fault before and after an earthquake. A parameter in many models of the earthquake source that has a bearing on the level of high-frequency shaking that the fault radiates.

Strike-slip fault - A fault whose relative displacement is purely horizontal.

Strong motion data – Records of strong ground motions from historical earthquakes; although strong is not universally or formally defined, it is often taken as accelerations of 0.1 g or larger, the threshold of damaging motions for many nonengineered structures.

Transpressional regime - A region with a mix of compressional (reverse) and strike-slip faulting.

ATTACHMENT II

PSHA SOFTWARE DESCRIPTION

PSHA SOFTWARE DESCRIPTION

The FRISK88 software package used for the PSHA (CRWMS M&O 1998a) calculations consists of four programs: PREP88 (version 1.0), FRISK88 (version 2.0), POST88 (version 1.0), and MRE88 (version 1.0). Program PREP88 is a preprocessor that prepares input to FRISK88, using information about the logic tree, the attenuation equations, and the seismic-source parameters and geometry. Typically, PREP88 is run separately for each seismic source. Program FRISK88 calculates the seismic hazard curves for each combination of input interpretations. FRISK88 also produces deaggregated seismic-hazard results. Program POST88 computes the total seismic hazard at the site, and sensitivity results, using the logic tree and the seismic-hazard curves from the various seismic sources. Another postprocessor, MRE88, calculates marginal and joint probability distributions and summary statistics of magnitude, distance, and ground motion for one or more seismic sources, using the deaggregated results produced by FRISK88. Programs DPREP (version 1.0) and DRISK (version 1.0) perform operations similar to those of PREP88 and FRISK88 for the calculation of fault displacements using the displacement approach. In addition, the combination of results from multiple teams and/or for multiple frequencies is performed by two small postprocessing utilities, namely MEAN and CMB-FRAC. The individual programs and algorithms used in the Yucca Mountain PSHA calculations are described further in the following sections. Note that the overall methodologies for the analyses and the terms used in these following sections are described further in Sections 6.3, 6.5, and 6.6. Note also that all input and output files referred to are located in DTN: MO0004MWDRIFM3.002.

1. PREP88

PREP88 (PREP88 V1.0, 10138-1.0-00) prepares input files for the FRISK88 program. Typically, PREP88 is run separately for each seismic source. The calculations performed by PREP88 involve only the generation of all branches of the logic tree (i.e., generate all possible combinations of parameter values) and the calculation of the associated probabilities.

The input to PREP88 consists of three parts, each contained in a separate file, as follows:

- **Attenuation File** (Contains the parameters of the attenuation-equations, as well as other information that is common to all seismic sources.

- **Logic-Tree File** (Defines the global parameters or interpretations that affect the characteristics of the seismic source (geometry, magnitude-recurrence, maximum magnitude [M_{max}]), the probabilities associated with each parameter or interpretation, and any probabilistic dependence among them.

- **Source File** (Contains information on how each source characteristic depends on the global parameters and interpretations that were specified in the logic-tree file.

The output from PREP88 consists of a FRISK88 input file and an echo file.

2. FRISK88

Program FRISK88 evaluates the probability that the earthquake ground motion at a site does not exceed specified amplitudes. This probability is evaluated by integrating all earthquake magnitudes, distances, and ground motion residuals. Typically, this calculation is performed separately for each seismic source. Alternative values of source parameters and geometry are input to represent their uncertainty. Each alternative parameter is given a weight to represent its credibility. FRISK88 can also be used for probabilistic fault-displacement calculations with the earthquake approach (see Section 6.3.4 for explanation of the earthquake and displacement approaches to assessing fault displacement).

The calculations performed by FRISK88 consist of numerical integration over three dimensions (earthquake magnitude, distance, and ground motion epsilon) as described in Equation 6-2. The calculations are performed for multiple values of the parameters that control the shape of the three functions in the integrand. Evaluation of the integral is performed by discretizing the range of earthquake magnitudes and locations within the seismic source and summing the contributions from each combination of magnitude and location. The algorithm does not involve iterative procedures, matrix inversion, numerical solution of systems of equations, or any other operation sensitive to instability or roundoff problems.

Input to FRISK88 consists of a file describing the alternatives for the geometry and magnitude distribution of the source, and the alternative attenuation equations. For areal sources with spatially varying seismicity, an additional input file contains the spatial distribution of seismicity. Output from FRISK88 consists of the following:

- **Echo File** (Contains a detailed echo of the program input.

- **Error File** (Contains error and warning messages.

- **Fractiles File** (Contains summary statistics (mean and fractiles) of earthquake hazard curves.

- **Hazard-Curve File** (Contains each hazard curve (exceedance probability vs. ground motion amplitude) that is calculated from each combination of source parameters and geometries, together with the weight associated with that curve.

- **Cryptic File** (Indicates the combination of parameters that correspond to each hazard curve in the Hazard-Curve File.

- **Magnitude-Distance-Epsilon (MRE [MRE88 V1.0, 10136-1.0-00]) Deaggregation File** (Contains the contributions of each MRE combination for one ground motion amplitude. (Epsilon is the ground motion residual.)

3. DPREP AND DRISK

Programs DPREP (DREP88 V1.0, 10141-1.0-00) and DRISK (DRISK88 V1.0, 10137-1.0-00) perform operations similar to those performed by PREP88 and FRISK88 for the displacement approach to fault displacement (see Section 6.3.4 for explanation of displacement approach).

The displacement approach calculates the probability of fault displacement in terms of displacement events at the site of interest, without considering earthquake magnitude or location. The integration in DRISK is performed using well-known approximations for the cumulative distribution function of normal, gamma, and exponential random variables. Input and output to and from DPREP and DRISK are organized in a similar manner to those of PREP88 and FRISK88 (except for the MRE file, which is not generated). The output from DRISK contains the total displacement hazard at the site. Running POST88 (POST88 V1.0, 10136-1.0-00) on the DRISK output is necessary only for the calculation of sensitivity results.

4. POST88

Program POST88 calculates the total hazard at the site by adding the hazard from all seismic sources, considering their uncertainty. The calculations performed by POST88 involve the generation of all branches of the global logic tree (i.e., generate all possible combinations of parameter values for all seismic sources), the calculation of the associated probabilities, the calculation of total hazard (from all seismic sources) for each branch of the logic tree, and the calculation of summary statistics.

Input to POST88 consists of the following files:

- **Control File** (Contains a list of the seismic sources, their associated file names, and instructions on how to simplify their logic trees, if appropriate. It also indicates which sensitivity analyses to perform.

- **Logic-Tree File** (Defines the global parameters or hypotheses that affect the characteristics of all seismic sources (geometry, magnitude-recurrence, M_{max}), the probabilities associated with each parameter or hypothesis, and any probabilistic dependence among them.

- **Hazard Curve and Cryptic Files** (Contains hazard curves for each seismic source.

Output from POST88 consists of an echo file, a fractile file, and files containing sensitivity results.

5. MRE88

MRE88 calculates marginal and joint probability distributions and summary statistics of magnitude, distance, and ground motion for one or more seismic sources. The calculations performed by MRE88 consist of bookkeeping and the calculation of summary statistics (e.g., means, standard deviations).

Input to MRE88 consists of the following files:

- **Control File (** Contains a list of the seismic sources and their associated file names.

- **MRE Deaggregation Files (** Contain deaggregated results for each seismic source.

Output from MRE88 consists of a file containing echo of the input, probability distributions of magnitude, distance and epsilon (trivariate, bivariate, and univariate), and summary statistics. These distributions are also output to separate files to facilitate plotting and tabulation of results.

6. UTILITY PROGRAMS (MEAN AND CMB-FRAC)

MEAN adds the mean hazards from multiple fractile files (and optionally normalizes them). It is useful for calculating the mean hazard from several sources or teams. Input to MEAN consists of a control file listing the names of the fractile files to use, the fractile files specified in the control file (fractile files are created by FRISK88, DRISK, and POST88), and an optional configuration file indicating the return periods to consider. Output from MEAN consists of a file containing a mean hazard curve.

CMB-FRAC combines the fractile hazard curves calculated for multiple expert inputs and computes fractiles using either equal or arbitrary weights. Input to CMB-FRAC consists of a control file specifying names of the fractile files to use (and optional weights), the fractile files specified in the control file, and an optional configuration file indicating the return periods to consider. Output from CMB-FRAC consists of a new fractile file containing the calculated fractiles, and a log file.